Development of nitrogen fertilization strategies in rice-wheat systems in southeastern China

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Zusammenfassung

Die Doppelfruchtfolge von überflutetem Nassreis (*Oryza sativa* L.) im Sommer und Weizen (*Triticum aestivum* L.) im Winter ist eines der bedeutendsten Anbausysteme Chinas und trägt als solches einen großen Teil zur Nahrungssicherung des Landes bei. Es ist geprägt durch eine sehr intensive Bewirtschaftungsweise mit minimalen Brachezeiten zwischen den beiden Kulturen, hohen Dünger-Stickstoff (N)-Gaben weit über dem N-Entzug, niedrigen N-Düngeeffizienzen und daraus folgend von sehr hohen N-Bilanzüberschüssen. Da es durch den regelmäßigen Wechsel zwischen nassen und trockenen Bodenbedingungen kaum zu einer Anreicherung des überschüssigen Stickstoffs im Boden kommt, sind die potentiellen N-Verluste aus den landwirtschaftlich genutzten Böden unter der Reis-Weizen Doppelfruchtfolge außerordentlich hoch.

Ziel dieser Arbeit war es, eine genaue Analyse der aktuellen landwirtschaftlichen Praxis bezüglich des N-Düngemanagements der chinesischen Kleinbauern durchzuführen und hieraus angepasste N-Düngestrategien abzuleiten, um bei möglichst gleich bleibendem Ertragsniveau die N-Düngeeffizienz zu erhöhen und die potentiellen N-Verluste in die Atmosphäre sowie in Grund- und Oberflächengewässer zu reduzieren. Hierfür wurden in zwei Regionen der Provinz Jiangsu praxisnahe Feldversuche auf bäuerlichen Schlägen über die Dauer von drei Jahren bzw. drei Reis-Weizen Doppelfruchtfolgen durchgeführt. In den Feldversuchen wurde dabei die gängige landwirtschaftliche Praxis und eine optimierte N-Düngestrategie bezüglich des Kornertrags, der N-Düngeeffizienz, der N-Bilanzüberschüsse und der Rest-N_{min}-Gehalte nach der Ernte miteinander verglichen. Daneben konnte durch die Anlage einer ungedüngten Nullparzelle ein genauer Einblick in die N-Dynamik des Systems Boden-Pflanze gewonnen werden.

Durch eine optimierte N-Düngestrategie bezüglich der gedüngten N-Menge und der Aufteilung der N-Einzelgaben, konnte in den Feldversuchen an beiden Standorten und in beiden Früchten die Gesamt-Dünger-N-Menge deutlich reduziert werden, ohne dass es zu einem Ertragsrückgang gekommen ist. Basierend auf den Ergebnissen der Feldversuche konnten in dieser Arbeit Empfehlungen für eine optimierte N-Düngung für die Reis-Weizen Doppelfruchtfolge in Ost- und Südostchina gemacht werden. Eine Minderung der Gesamt-N-Menge um 15 bis 25 % für Reis bzw. um 20 bis 30 % im Weizen wird empfohlen. Es hat sich gezeigt, dass das größte Minderungspotential für die N-Düngung bei der extrem hohen N-Gabe zur Grunddüngung zum Weizen bzw. in den frühen Wachstumsstadien zum Reis besteht. Durch die reduzierte N-Düngung konnten die N-Bilanzüberschüsse um 90 kg N ha^{-1} in Süd Jiangsu und um mehr als 140 kg N ha^{-1} in Nord Jiangsu reduziert werden. Zudem konnten die betrachteten N-Düngeeffizienzen deutlich verbessert werden, was auf eine bessere Ausnutzung des Dünger-N schließen lässt. Die untersuchten Rest-N_{min}-Gehalte nach der Ernte konnten mit einer optimierten N-Düngung gerade im Weizen deutlich gesenkt werden.

Ein weiterer Teil der Untersuchungen in Nord Jiangsu war es, das Potential für eine nachhaltigere Behandlung der Erntereste zu untersuchen. Durch die nach wie vor häufig durchgeführte

Verbrennung des Strohs der Vorfrucht direkt auf dem Feld kommt es zu dem Verlust von organischen C- und N-Verbindungen, die potentiell zur Verbesserung der Bodenfruchtbarkeit beitragen würden. Außerdem kommt es durch die Strohverbrennung nach der Ernte zu einem erheblichen Anstieg der Feinstaubkonzentrationen. In dieser Arbeit konnte gezeigt werden, dass die Einarbeitung von Reisstroh vor dem nachfolgenden Winterweizen gut durchzuführen ist und es zu keinen negativen Einflüssen auf die Kornerträge und die Bestandsentwicklung kommt. Dagegen ist die Einarbeitung des Weizenstrohs vor der Reisfrucht wegen der kürzeren Brachezeit zwischen den Kulturen mit einigen Schwierigkeiten verbunden und kann potentiell zu einem Anstieg der Methan- und Ammoniakemissionen aus dem überfluteten Reisfeld beitragen.

Neben der genauen Untersuchung der aktuellen N-Düngepraxis und der Entwicklung von optimierten N-Düngestrategien, wurde in dieser Arbeit als eine weitere, spezielle Maßnahme zur Minderung der N-Verluste und Verbesserung der N-Düngeeffizienz, das Minderungspotential des Nitrifikationsinhibitors DCD in Kombination mit Harnstoff für den Einsatz in der Reis-Weizen Doppelfruchtfolge im Norden der Provinz Jiangsu getestet. Dabei hat sich gezeigt, dass sich die Wirksamkeit des Nitrifikationsinhibitors zwischen den beiden Kulturen unterscheidet. Der Effekt auf Kornertrag und N-Aufnahme war beim Winterweizen deutlich ausgeprägter als beim überstauten Sommerreis. Dieser Effekt war jedoch stark von den Wetterverhältnissen nach der N-Düngung abhängig, was sich auch in den untersuchten N_{min}-Gehalten im Boden vor den jeweiligen N-Düngergaben gezeigt hat. Die Untersuchungen im Reis haben dagegen gezeigt, dass die N-Aufnahme und die N-Düngereffizienz durch den Nitrifikationsinhibitor zwar leicht erhöht werden konnten, es im Vergleich zur mit Harnstoff gedüngten Variante aber keinen eindeutigen Effekt auf den Kornertrag gab. Ein Effekt des Nitrifikationsinhibitors auf die N_{min}-Gehalte im Boden während des Sommerreisanbaus konnte nicht beobachtet werden.

Die Ergebnisse dieser Arbeit verdeutlichen das große Minderungspotential für die mineralische N-Düngung in der Reis-Weizen Doppelfruchtfolge in China. Es werden optimierte N-Düngestrategien entwickelt mit denen die potentiellen N-Verluste in die Atmosphäre sowie in Grund- und Oberflächengewässer signifikant reduziert werden können. Eine deutliche Verbesserung der N-Düngeeffizienz ist durch eine gezieltere Anpassung der N-Menge der einzelnen Düngergaben an den Pflanzenbedarf und die Wetterverhältnisse zu erreichen. Daneben konnten in dieser Arbeit weitere Strategien zur Minderung der Umwelteinflüsse der Reis-Weizen Doppelfruchtfolge, wie den Einsatz eins Nitrifikationsinhibitors und die Möglichkeit der Stroheinarbeitung aufgezeigt werden.

Summary

The rice-wheat double crop rotation of irrigated summer rice (*Oryza sativa* L.) and a winter upland crop, mainly winter wheat (*Triticum aestivum* L.) is one of the most important cropping systems and essential for maintaining food security in China. It is characterized by a highly intensive crop management with short fallow periods between the two crops, high fertilizer nitrogen (N) application rates exceeding the crop N uptake, low N use efficiencies and, thus, extremely high N balance surpluses. Because the periodical shift between wet and dry soil conditions induces low accumulation rates of the surplus N in the soil, the potential N losses from the agricultural soils under the rice-wheat double crop rotation are exceptionally high.

The aim of this thesis was to evaluate the current agricultural practice regarding N fertilizer management of Chinese small-scale farmers and deduct adapted N fertilizer strategies in order to increase the N use efficiency and reduce the potential N losses to the atmosphere as well as ground and surface water at a constant yield level. Therefore, on-farm field trials were conducted on farmers' field sites for three years, corresponding to three rice-wheat double crop rotations, in two regions in Jiangsu Province. In these field trials, the current agricultural practice was compared to an optimized N fertilization management with respect to grain yield, N fertilizer efficiency, N surplus and residual N_{min} content after harvest. The installation of an unfertilized "zero N" treatment enabled the investigation of the N dynamic in the soil-plant system.

The total N fertilizer application rate could be significantly reduced without yield decrease at both sites and for both crops due to an optimized fertilizer N management regarding N fertilizer application rate and split applications. Based on the field trials' results, recommendations for an optimized fertilizer N management of the rice-wheat double crop rotation in east and southeastern China could be developed in this thesis. A reduction of the total N fertilizer amount by 15 to 25 % and 20 to 30 % is recommended for rice and wheat, respectively. It was shown, that the largest reduction potentials exist for the basal N fertilizer application, which is commonly extremely high, and in the early growth stages of the summer rice. The N balance surpluses could be reduced by 90 kg N ha^{-1} in south Jiangsu and by more than 140 kg N ha^{-1} in north Jiangsu by applying the reduced N fertilization. Additionally, the regarded N fertilizer efficiencies were significantly enhanced, pointing to an improved utilization of the applied fertilizer-N. The residual mineral N contents after harvest could be significantly reduced by an optimized fertilizer N management, in particular for the wheat crop.

Further investigations in northern Jiangsu Province were conducted in order to investigate a more sustainable management of crop residues. With the frequently practiced burning of the previous crop's residues directly on the field, organic C and N that could potentially contribute to increasing soil fertility and plant nutrition, is lost to the atmosphere. Additionally, the concentration of particulate matter in the air increases drastically by straw burning after harvest. It could be shown, that the incorporation of rice straw before the proceeding wheat crop could easily be performed and

no negative effect on grain yield or crop establishment were observed. In contrast, the management of wheat residues during irrigated lowland rice presents a considerably bigger challenge due to the very short fallow period between wheat and rice. Additionally, it can potentially stimulate methane emissions and increases ammonia volatilization after urea application.

Additionally to the evaluation of the potential environmental impact of current fertilization practices and to the development of optimized fertilization strategies, the application of urea in combination with the nitrification inhibitor DCD was tested as an option to stabilize the applied N and to enhance the N use efficiency and reduce N losses in the rice-wheat system in northern Jiangsu. The results showed that the use of a NI had a more pronounced effect on grain yields and N use efficiency on winter wheat compared to summer rice. However, the effect on winter wheat's crop growth was highly influenced by the weather conditions after fertilizer-N application that was in congruence with the observed mineral N contents in the soil before fertilizer application. For rice, the results showed a slightly higher crop N uptake and N use efficiency due to the application of the nitrification inhibitor. However, compared to the fertilization with pure urea, there was no significant effect on grain yields and an influence of NI addition on soil mineral N contents during the summer rice season could not be observed.

The results of this thesis clearly reveal a huge reduction potential for the mineral N fertilization in the rice-wheat double cropping system in China. The developed optimized fertilization strategies can contribute to significantly reduce the high potential N losses to the atmosphere and to fresh water bodies. A distinct higher N use efficiency can be achieved with a better adaption of the fertilizer application to crop N demand and weather conditions. Moreover, with the investigation of nitrification inhibitor application and the possibilities for crop residue incorporation, further strategies to reduce the impact of the rice-wheat rotation on the environment could be demonstrated.

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1. Introduction

1.1. Intensive Chinese agriculture

China is the most populated country in the world with a population of 1.38 billion in 2015 (UN 2015). Its agriculture has to provide enough food for 22 % of the world's population with only 9 % of its arable land (FAO 2014) and since a large famine in the late 1950s, food security via grain self-sufficiency is a highly promoted goal. Considerable efforts were made to achieve this goal with the implementation of broad institutional reforms in the late 1970s and with the introduction of modern agricultural production methods (Carter et al. 2012). One of the most important components of the reforms was the privatization of land use rights that improved farmers´ incentives to achieve higher yields. Thus, the overall productivity increased significantly in the early years of the reforms. Moreover, dwarf and semi-dwarf varieties of rice and wheat were introduced in the 1960s, followed by hybrid rice in the 1970s, and significant varietal improvements in all major field crops were performed since the 1980s (Carter et al. 2012). At the same time, crop rotations were intensified and modern production methods such as the use of synthetic fertilizers, pesticides, irrigation and agricultural mechanization increased significantly (Zhu and Chen 2002). As a result of these changes, the productivity of Chinese agriculture grew by more than 300 % from 1978 to 2009 and total grain production increased from 110 Tg yr^{-1} in 1961 to 429 Tg yr^{-1} in 2005 (Xiong et al. 2008). Grain yields per ha of the three major field crops, rice, wheat and maize, increased by 66, 157 and 88 %, respectively, from 1978 to 2009. Nevertheless, due to the rising living-standard of a growing middle-class and a change in diet, China cannot rely on its own food production anymore and has become the world's largest importer of agricultural products in 2011 (WTO 2015). This is mostly caused by the high demand for feed grains (maize) and soybeans while it is of highest priority for China to maintain at least 95 % self-sufficiency in basic food grains. Therefore, the pressure on the major crop growing area is dramatically increasing.

This development is aggravated by the continuous decline of the area of arable land for crop production due to the further ongoing urbanization and industrialization. Arable land in China declined from 130 Mha in 1996 to 121.7 Mha in 2007, or by 6.4 %, although control mechanisms have been implemented to prevent the land-use change from farmland to non-agricultural use (MOA and FAO 2012). Moreover, land losses occur mainly in areas with high-quality arable land in the south and south-eastern Provinces and these areas being frequently replaced by marginal or lower-quality land such converted forests or grasslands in the north that are often ecological fragile zones (Kong 2014). Two-thirds of the total arable land in China is already classified as medium- or low-yielding land (Carter et al. 2012) and in order to produce more food on less land, the remaining high-quality arable land is highly overused in case of cropping intensity and inputs of fertilizers and pesticides. Most affected by this development are the strongly urbanized coastal regions of China in the provinces Jiangsu, Zhejiang, Fujian and Guangdong. Here the losses of arable land from 1996 to 2009 of between 5.9 and 13.5 % and losses in productivity capacity (measured by annual grain yield equivalents) between 9.1 and 17.7 % (Carter et al. 2012). The most important cropping system in the coastal region of China but also in the middle reaches of the Yangtze River is the rice-wheat double cropping system.

1.2. The rice wheat double-cropping system

The rice-wheat double-crop rotation is one of the most important cropping-systems in Asia due its high productivity and its widespread distribution. It is essential for maintaining food security, especially in densely populated regions in India, Bangladesh and China. Most rice-wheat areas are located in South and East Asia within the warm-temperate and subtropical climate, characterized by cool, dry winters, and warm, wet summers (Figure 1.1). First recordings for this double-crop rotation in the Yellow River Basin date back to the Tang Dynasty (617-907 A.D.) (Huke et al. 1994) but the importance of this system grew constantly since the 1960s with the advent of the Green Revolution (Huke et al. 1994; Timsina and Connor 2001). The development of short-duration varieties of rice and wheat enabled both crops to be grown in one year even in regions where this was not possible before, leading to the substantially increasing extension of the rice-wheat zones. However, the reported area planted to the rice-wheat rotation in China differs substantially ranging from 3.4 Mha, estimated by Dawe et al. (2004) for 2001 based on official statistics and remote sensing data, to 10 Mha and 13 Mha reported by Ladha et al. (2003) and Zheng (2000), respectively, who did not give any details about the estimation method and the specific year for which the estimation is valid. In China, the rice-wheat double cropping system is concentrated between 28°N and 35°N, mostly along the Yangtse River Basin in the Provinces Jiangsu, Zhejiang, Hubei, Guizhou, Yunnan, Sichuan and Anhui, but it is also found as far as 40°N across the Huaihe and the Yellow River (Huke et al. 1994; Zheng 2000).

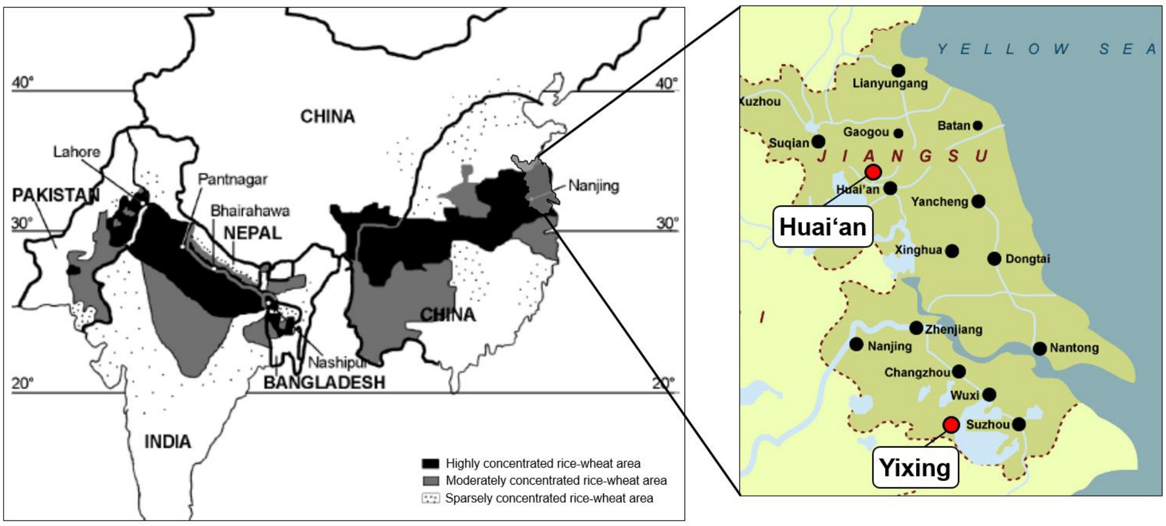

Figure 1.1: Left map: Distribution of rice-wheat areas in south Asia and China (adapted from Timsina and Connor 2001). The curve passing from northeast to southwest China represents the limits for rice-wheat cropping systems in China. Right map: Map of Jiangsu Province, China with the two experimental sites in Yixing and Huai'an (red dots).

For summer rice grown in a rotation with an upland crop during the winter, the growing season is longer in the south than in the north and the system can also include a third crop in the south such as a second rice crop, sweet potato or green manure (Timsina and Connor 2001). In contrast, the growing season for winter wheat in the coastal regions of China is shorter in the south (from early November to mid-May) than in the north (from early October to mid-June). Field preparation for the rice crop starts shortly after wheat harvest with flooding the field followed by puddling the waterlogged soil and levelling the land. Summer rice is transplanted on nearly 90 % of the total rice area (Zhu 2011), using seedling from nurseries established 3-4 weeks earlier. Transplanting is traditionally done by hand, although seedling throwing and mechanical transplanting are practiced on roughly 20 % of the rice area (Zhu 2011) each and are increasingly promoted, due to the eased cultivation and economic benefits caused by lower labour costs. Moreover, direct-seeding of rice is carried out on nearly 10 % of the rice area (Zhu 2011) especially in regions with high economic growth and labour scarcity like the Taihu Region in Jiangsu Province. However, there is no statistical data available on the area of the different cultivation practices in the rice-wheat system. All rice varieties grown in China are modern high-yielding varieties (including hybrid varieties) with an average grain yield of about 6.5 Mg ha^{-1} (GRiSP 2013). During the rice season, the water level is maintained at 5-10 cm and the fields are usually drained at late tillering stage for 1 to 2 weeks (mid-term aeration) and flooded again at panicle initiation until early ripening stages. The rice is harvested between end of October and early November with combine harvesters and crop residues are removed, chopped and incorporated during field preparation for the winter wheat crop or burned directly on the field. Field preparation for the winter wheat crop consists of shallow tillage and digging of drainage ditches in order to increase soil permeability and aeration for the wheat crop. Soil conditions during the winter season in fields under the rice-wheat rotation are usually comparable wet.

1.3. Nitrogen fertilization in China

1.3.1. Trends in nitrogen fertilization

Agricultural practices in China and in particular fertilizer management changed sharply in the past four decades. Traditional agroecosystems were characterized by complex crop rotations with an almost complete recycling of organic materials as the most important source of nutrients for crop and vegetable production. With the use of extremely labour-intensive fertilizers such as the “oufei” compost in the Taihu Region, an anaerobically fermented mix of canal sediments, legume green manures, crop residues and animal manures, agriculture remained productive at a constant or even increasing level, while maintaining soil productivity for centuries (Ellis and Wang 1997; King 1911; Roelcke et al. 2005). Organic manure provided nearly 100 % of the total nutrient input to the Chinese agriculture until the early years of the P.R. China (Cheng and Wen 1997). However, since the introduction and promotion of mineral N fertilizers by the Chinese government in the 1960s, the use of organic N from human and animal excreta as well as from crop residues was constantly declining to only 35 % in 2001, accounting for 18 % of overall N applied in agriculture (Zhang et al. 2006). A survey on farmers’ fields in Changshu, Jiangsu Province, by Zhu and Chen (2002) for example showed that the average application of organic manure to flooded rice was around 50 kg N ha^{-1} in 1986 (accounting for 30 % of total N applied) and declined to only 20 kg N ha^{-1} in 1997, accounting for 6.7 % of the total applied N. However, despite the drastically declined use of organic manure in crop production, the accruing total amount of manure increased substantially due to the growing livestock numbers in the past two decades.

The consumption of nitrogenous fertilizers in China increased dramatically from the mid-1970s on. While 4.75 Tg N were applied to Chinese cropland in 1976 the amount increased to 30.12 Tg N in 2013 (Ministry of Agriculture 2014), which amounted to 30 to 33 % of the world total N fertilizer consumption (FAO 2014). This increase of fertilizer consumption in China accounts for 90 % of global increase in fertilizer use since 1981 (Liu and Diamond 2005). China has been the world´s largest consumer of N fertilizer since 1979 and its consumption is higher than that of the United States of America and the European Union together since 1995. Moreover, the application of mineral N fertilizers per hectare far exceed those in the United States and Europe considerably (Vitousek et al. 2009). This development has been enhanced by high governmental subsidies for the production and transport of mineral fertilizers (Ju et al. 2009; Zhu et al. 2006). Average N application rates for the three main crops in China were reported from a broad farmers´ survey by Cui et al. (2014c) and were 214 (95-479 kg N ha^{-1}), 284 (102-573 kg N ha^{-1}), and 229 kg N ha^{-1} (102-552 kg N ha^{-1}) for rice, wheat, and maize, respectively. In 2010, the mean fertilizer N application rate in China per crop was 183 kg N ha^{-1} (Hartmann et al. 2014; Ju et al. 2009; Liu et al. 2003; Xu et al. 2009; Zhao et al. 2006), which is the highest worldwide. The increased N fertilizer use has contributed substantially to the highly needed increase in food production in the last four decades in China. However, high portions of applied nutrients cannot be utilized by the crops and are potentially released to the environment as pollutants, particularly in the most populous and intensive agricultural areas in eastern and southeastern China (Ma et al. 2012).

1.3.2. Nitrogen use efficiency in Chinese crop production

The extremely high N fertilizer application rates commonly reported for Chinese crop production usually failed to achieve a good temporal congruence between nutrient supply and the crop nutrient demand and only a small portion of the applied N is efficiently used by the crop. Hence, the N use efficiency (NUE) of main cropping-systems in China steadily decreased since the broad introduction of synthetic N fertilizers in the 1970s. The NUE of agricultural systems is a broad term that generally describes the crop response to N fertilization. Crop response can be indicated as, e.g., the ratio of grain yield to the amount of applied fertilizer N (partial factor productivity, PFP_N), the yield increase per kg N applied (agronomic efficiency of applied N, AE_N) and the increase in aboveground N per kg of N applied (recovery efficiency, RE_N). The most comprehensive measure of NUE is the PFP_N, which is an aggregated efficiency index that includes the contribution to yield formation by indigenous soil N, fertilizer N recovery and the efficiency of the crop to convert acquired N to grain yield. In a survey of more than 6000 farmers in the two most important double-cropping systems in China, the wheat-maize system in the North China Plain (NCP) and the rice-wheat system in the Yangtze River Valley, the PFP_N was only 37, 25 and 32 kg kg^{-1} for rice, wheat and maize, respectively (Cui et al. 2014c). The PFP_N of grain production in China decreased from 100 kg kg^{-1} in 1978 to only 31 kg kg^{-1} in 2010 (Li et al. 2013) that is clearly lower compared to the common values for cereal production ranging between 40 and 70 kg kg^{-1} (Dobermann 2005). In contrast to the PFP_N, the AE_N specifically indicates the efficiency of fertilizer N application in regard to grain yield. Based on the results of a total of 368 field trials within the main field crops in China by Li et al. (2013), the mean AE_N for rice, wheat and maize was reported to be 12.6, 8.3 and 11.5 kg kg^{-1}. This shows clearly that the AE_N of crop production in China is extremely low, if not the lowest in the world. The average AE_N of rice, wheat and maize in a worldwide evaluation by Ladha et al. (2005) had a relatively narrow range between 18 and 24 kg kg^{-1} and was smallest in maize and largest in rice. Similar to the AE_N, the RE_N also indicates the efficiency of N fertilization but with regard to the fertilizer N recovered in the aboveground biomass at maturity. Results of ^{15}N experiments indicate very low RE_N for all major field crops in China with differences for the winter wheat crop within the maize-wheat and the rice-wheat double crop rotations (Ju et al. 2009). The reported RE_N for rice and maize was 0.30 and 0.26 kg kg^{-1}, respectively, while the RE_N for winter wheat was 0.31 and 0.18 kg kg^{-1} within the maize-wheat and the rice-wheat rotation, respectively. However, Zhang et al. (2014) reported an overall average RE_N for the three main crops of 0.3 to 0.35 kg kg^{-1}.

1.3.3. Nitrogen balance surpluses and nitrogen loss potential

The combination of high fertilizer N application rates with the low ability of the crops to acquire the applied N and utilize it for total plant biomass or grain production, led to extremely high N balance surpluses. Nitrogen balances (or budgets) are a valuable tool to indicate the N loss from agricultural production systems (Legg and Meisinger 1982) and to estimate the N loss potential of agricultural production on different scales. However, it is not possible to obtain which environmental compartment (soil, aquifers or atmosphere) is affected by the N surplus and to what extent. At the national scale Gu et al. (2015) recently reported integrated N budgets for 14 different subsystems in China for 1980 and 2010. Based on these figures, the national N surplus from Chinas agricultural sector (crop and livestock production) increased from 15 Tg N yr^{-1} in 1980 by more than 2.4 times to 36 Tg N yr^{-1} in 2010. The share of crop production in the overall agricultural N surplus is nearly 80 % and that of livestock production approximately 20 % but with an increasing trend. Most important N inputs to the national N balance are synthetic N fertilizers with 65 % of the total N input of 47 Tg N yr^{-1}. According to Gu et al. (2015), nearly 60 % of the surplus N is lost to the atmosphere (as NO_x, NH_3, N_2O and N_2), 20 % to the hydrosphere (via surface run-off and leaching) and 20 % accumulate in the soil.

Compared to national N balances, changes in agricultural production systems, land use patterns, regional variations and effects on the environment can be better monitored with N balances at a regional level. Ma et al. (2012) calculated N balances of crop production at a provincial level for the years 1980 and 2005. They reported that the mean N surplus of the 31 Provinces increased from 81 to 220 kg N ha^{-1} with very large regional differences. While national and regional N balances and the N surplus in particular is generally used as an agri-environmental indicator for analyzing the environmental performance of agriculture as a whole, nutrient balances at farm, field or cropping-system level provide more information about specific farming practices or farm types. Recently reported N balance surpluses under current farmers fertilization practice for the two most intensive cropping systems, the maize-wheat system in the NCP and the rice-wheat system in south eastern China, were up to 262 kg N ha yr^{-1} (Hartmann et al. 2014) and 284 kg N ha yr^{-1} (Hofmeier et al. 2015), respectively.

1.4. Environmental impact of current nitrogen fertilization

The inefficient use of fertilizer-N and the extremely high N balance surpluses of the major cropping-systems in China are an indicator for the high N loss potential of the current agricultural practice. All N lost from the soil-plant system is a potential source of environmental pollution. On its way through this system, N undergoes various transformation processes, can escape via different loss pathways to water bodies and the atmosphere and can have a high environmental impact in the respective environmental compartments. Main N loss pathways are (1) run-off and leaching of predominantly as nitrate (NO_3^--N) and partially ammonium (NH_4^+-N) and dissolved organic N (DON), (2) ammonia (NH_3) volatilization and (3) emissions of nitrous oxide (N_2O), nitric oxide (NO) and dinitrogen (N_2) during nitrification and denitrification. The environmental impact of agricultural N losses from N fertilization practices are listed in Table 1.1.

Table 1.1: N loss pathways from soil-plant system and corresponding environmental impacts (Ladha et al. 2005, modified).

N loss pathway		Environmental impact
Run-off, erosion	→	Surface water eutrophication
Nitrate leaching	→	Groundwater contamination
Ammonia volatilization	→	N-deposition and acidification
Nitrous oxide emissions	→	Global warming
Nitrous oxide and nitric oxide emissions	→	Ozone depletion

1.4.1. Hydrospheric nitrogen emissions from agricultural soils

Nitrogen emissions from agricultural soils to the hydrosphere have caused a poor and still declining water quality in most Chinese rivers and aquifers, and nutrient run-off and erosion from agricultural fields caused widespread eutrophication (Conley et al. 2009; Gu et al. 2013; Liu and Diamond 2005). The total N load from Chinese agriculture to the hydrosphere increased since 1980 by 2.4 Tg N to annual emissions of 7.8 Tg N yr^{-1} in 2010 (Gu et al. 2015). Measured N-losses via run-off and leaching in field experiments indicate substantial differences between the three major field crops (Table 1.2). Nitrogen losses from the soil via leaching is relatively small in rice fields, due to the restricted percolation caused by the hard pan under the plough layer formed by the puddling the flooded soil. Reported N leaching losses are usually lower than 10 kg N ha^{-1} and mean N losses do generally not exceed 3 % of the applied fertilizer-N. Average N losses via run-off from rice fields are only slightly higher but can increase dramatically during heavy precipitation events. Considerable N run-off losses during the wheat season in a rice-wheat rotation are favoured by the drainage ditches in the field during the winter wheat season and can be as high as 60 kg N ha^{-1} or 30 % of applied N (Zhao et al. 2012a). Leaching losses in this rice-upland cropping system can be high after the wheat crop, when the soil is flooded for the subsequent rice crop because the residual NO_3^--N is prone to losses (Gaydon et al. 2012; Ladha et al. 2005; Roelcke et al. 2002; Roelcke et al. 2004). In contrast to the leaching losses from paddy fields, N leaching in upland cropping systems (wheat-maize) is distinctly higher and can be considered as a major loss pathway with N losses of 10-15 % of the applied N during winter wheat season and of up to 30 % during the summer maize season. Leaching losses are favoured by flood irrigation practice in the maize-wheat rotation and by heavy rainfall events during summer and autumn (Cui et al. 2014c).

Table 1.2: Nitrogen run-off and leaching (in kg N ha^{-1}) from major field crops in China.

Crop	N run-off	N rate	N leaching	N rate	Reference
Rice	11.0 (0−65.7)	205 (12-405)	5.7 (0.7−18.6)	192 (81-360)	Cui et al. (2014c)
	6.9 (2.5-16.9)	252 (184-324)	7.6 (3.3-14.4)	252 (184-324)	Yang et al. (2013)
			7.9	300	Cao et al. (2014)
			4.4 (3.8-5.1)	243 (135-405)	Qiao et al. (2013)
Wheat			20.1 (0−200.0)	199 (55-450)	Cui et al. (2014c)
			22±24, 48±32	200	Fang et al. (2006)
			30.2 (3.6-83.9)	180 (90-360)	Liang et al. (2008)
	23.5 (10.6-38.6)	191 (135-248)			Tian et al. (2007)
Maize			47.2 (0−233.0)	213 (30-400)	Cui et al. (2014c)
			58±10, 118±25	200	Fang et al. (2006)

1.4.2. Atmospheric nitrogen emissions from agricultural soils

The largest source of reactive N in the atmosphere in China is the emission of ammonia (NH_3) from agricultural soils and from animal and human manure management, while other sources are negligible (Liu et al. 2013b; Shi et al. 2015; Zhang et al. 2010). In 2010, reported NH_3 emissions from agriculture amounted to 12.3 Tg NH_3-N yr^{-1}, including 7.7 Tg NH_3-N yr^{-1} from crop production (mainly volatilization of applied fertilizer-N) and 4.6 Tg NH_3-N yr^{-1} from livestock production (Gu et al. 2015). The NH_3 emissions are very uneven distributed within China. High emissions were reported from the Provinces Shandong and Jiangsu as well as some parts of Hebei and Henan, which is consistent with the heavy fertilizer N application in these intensive agricultural areas (Zhang et al. 2010). Ammonia volatilization losses of fertilizer N are favoured by the common practice of surface application of urea-N into the ponded water (Cao et al. 2013; Freney 1997; Vlek and Craswell 1981) and by high temperatures and high soil pH (Sommer et al. 2004) which both are often present under subtropical rice-wheat rotations and. As shown in Table 1.3, measurements during the rice season in this cropping system usually resulted in NH_3 losses of between 20 to 25 % of applied fertilizer-N (Fan et al. 2006; Yang et al. 2013; Zhao et al. 2012a). Volatilization losses during the wheat season are considerably lower (Ju et al. 2009), but N losses of up to 14 % of applied N have been reported by Zhao et al. (2012b). Ammonia volatilization during the maize-wheat double crop rotation in the NCP is equally estimated to be another main loss pathway next to leaching of NO_3^--N and NH_3 losses of up to 20 and 25 % of fertilizer N were reported for winter wheat and summer maize, respectively (Ju et al. 2009). However, under conditions with a high N loss potential NH_3 losses can account for up to 40 % of applied N and 70 % of total gaseous loss (Cai 1997). The higher NH_3 loss potential of the upland maize-wheat rotation is also emphasized by the fertilizer-N emission factors of 30 % estimated by Zhang et al. (2010) in a NH_3 emission inventory for the NCP. The estimated emission factor for the rice-wheat rotation was 22 %.

Table 1.3: NH_3 volatilization and N_2O emissions (in kg N ha^{-1}) from major field crops in China.

Crop	NH_3	N rate	N_2O	N rate	Reference
Rice	33.9 (4.8−125.3)	194 (41−403)	1.4 (0−6.3)	199 (42−450)	Cui et al. (2014c)
	40.4 (17.9-80.8)	135			Fan et al. (2006)
	34.8	300			Ju et al. (2009)
	25 (13.8-50)	150			Lin et al. (2007)
	70 (68.2-71.7)	314			Yang et al. (2013)
	76.1 (60-96.9)	300			Zhao et al. (2012b)
Wheat	23.8 (0.5−63.1)	172 (34−355)	0.9 (0.1−2.4)	178 (52−300)	Cui et al. (2014c)
	5.3; 63.1	250; 325			Ju et al. (2009)
	27.1 (10.6-50.6)	200			Zhao et al. (2012b)
Maize	34.6 (4.0−77.0)	137 (20−300)			Cui et al. (2014c)
	64.9	263			Ju et al. (2009)

Nitrogen losses to the atmosphere are also caused by nitrification and denitrification pathways. Agriculture indeed is the most important source of N_2O emissions and food production being likely responsible for 80 % of the increase in atmospheric N_2O since the 1960s due to the high increase in consumption of N based fertilizers (Davidson 2009; IPCC 2014; Park et al. 2012). Estimated N_2O emissions from agricultural soils in China are 0.4 Tg N_2O-N yr^{-1} (Gu et al. 2015) or nearly one tenth of the global N_2O emissions from agriculture that are approximately 4.1 Tg N_2O-N yr^{-1} (Oenema et al. 2013).

1.5. Strategies to mitigate N emissions to the environment

There is no doubt that the NUE of Chinese intensive cropping-systems has to be significantly increased in order to markedly decrease N balance surpluses, N losses to the environment, and economic losses for farmers. In order to achieve this, optimized fertilizer, soil and crop management strategies have to be implemented on a large scale. It is imperative that these strategies can easily be realized by small-scale farmers' and that they have no negative impact on grain yield or farmers' income. However, a lack of information about new management practices, very scarce farmers' professional education and an insufficient agricultural extension service system in China (Hu et al. 2009) make the implementation of optimized agricultural practices very difficult.

Several concepts to optimize crop NUE and reduce N losses were developed in the recent years for cropping-systems with high fertilizer N input. Most of these concepts are based on a better consistence between crop N demand and N supply. One of the most widely used concepts is the site specific nutrient management (SSNM) approach developed by the International Rice Research Institute (IRRI) for irrigated rice with its key components of an improved N management and a balanced fertilization (Fairhurst et al. 2007). Significant increases in grain yield and NUE could be achieved with SSNM compared to farmers practice (Dobermann et al. 2004). This approach is based on measuring the leaf N status at certain growth stages with a chlorophyll meter (SPAD) or the leaf colour chart (LCC) and to adjust predetermined topdressing N fertilizer applications in real-time to the site-specific needs of a rice crop. A review given by Peng et al. (2010) about the use of SSNM in six rice growing-provinces in China showed that N fertilizer application rates could be reduced by 32 % and grain yield increased by 5 % with SSNM compared to the farmers practice. A reduction of crop damage by pests and insects was investigated and lodging resistance was improved under optimal N rates. Moreover, the average PFP_N (as an indicator for the NUE) in 107 on-farm demonstration experiments from six provinces in China increased by 43 % to 56 kg kg^{-1} under SSNM (Peng et al. 2010).

Another concept to improve NUE, increase crop productivity and reduce environmental costs is the approach of integrated nutrient management (INM) that has originally been developed for the intensive maize-wheat double-crop rotation in the NCP and was recently applied to other cereal, vegetable and fruit cropping-systems (Zhang et al. 2012). According to this approach, the total amount of N fertilizer is divided into two or three split applications and the respective optimal N rates are determined with the help of soil NO_3^--N tests in the root zone. The key components of the INM are to consider all possible nutrient sources for determination of fertilizer N demand (organic and mineral N sources as well as N deposition, N in irrigation water and biological N fixation), to match the nutrient supply in the root zone with the crop requirements and to take other possible measures for increasing grain yield into account (best available practice for crop and pest management). The INM has been tested in numerous field experiments in the NCP and it was shown that grain yield could be maximized with a significantly reduced environmental impact (Chen et al. 2011; Cui et al. 2010a).

To consider all N sources, such as green manure, animal manure, crop residues, native soil N and inorganic fertilizers, and their specific N supply pattern is the basis for improving the NUE and minimizing environmental impacts (Zhu and Chen 2002). While input of inorganic N with mineral N fertilizers increases the mineral N pool of the soil immediately and therefore usually has a high availability for plants, organic N sources have to be mineralized before becoming plant available. The mineralization rate of soil N is strongly dependent on factors such as temperature, water regime and the C/N ratio. Nitrogen mineralization in flooded tropical rice soils can range from 52 to 107 kg N ha^{-1} for one cropping season (Kundu and Ladha 1995) and the N supply rate can range from 0.3 to 1.2 kg N ha^{-1} d^{-1} with a total N mineralization of 70 to 80 kg N ha^{-1} season^{-1} (Ladha et al. 2005). Nutrient release from incorporated organic material depends on residue type, length of decomposition period, climatic conditions and soil temperature and moisture. For green manure or leguminous crop residues with a C/N ratio of 10 to 15 applied to flooded soils, most of the nutrients are released within 2 to 4 weeks (Becker et al. 1995). In comparison, the decomposition of crop residues with a wider C/N ratio takes much longer. Cheng and Wen (1998) reported that nearly 70 % of the rice straw were decomposed after one rice-wheat rotation (1 year) in China and 90 % were decomposed after 10 years. However, Cassman et al. (1998) reported that the N contained in rice straw had a fertilizer-N equivalent of about 85 %, when straw was incorporated in combination with mineral N fertilizer.

Other strategies to increase the NUE and to mitigate N losses to the environment focus on the stabilization of applied fertilizer-N. This is most effective for ammonium-based fertilizers and urea, as the positively charged ammonium ions are retained by the soil colloids and are less susceptive to leaching and denitrification losses. The stabilization of these fertilizers can either be achieved by deep-placement of urea or urea supergranules (Rees et al. 1996; Sudhakara and Prasad 1986), by a banded, sub-surface application of concentrated ammonium-based fertilizers (Sommer and Jensen 1994) or by the stabilization of ammonium-N with nitrification inhibitors such as dicyandiamide (DCD) or 3,5-dimethylpyrazolephosphate (DMPP) (Subbarao et al. 2006). The application of these inhibitors can increase both crop yield and NUE (Prasad and Power 1995) and can also have a considerable influence on nitrous oxide (N_2O) and methane (CH_4) emissions from the soil (Bhatia et al. 2010; Boeckx et al. 2005; Malla et al. 2005; Pathak et al. 2003).

1.6. Objectives of this thesis

A sustainable intensification of Chinese agriculture is essential for maintaining food security without negative impacts on water bodies and atmosphere. One of the most crucial factors to achieve this goal is the proper management of N fertilizers. Therefore, the aim of this thesis is to investigate and demonstrate N mitigation options for the rice-wheat double cropping system in eastern and southeastern China, which is one of the most intensive cereal-cropping systems of the world. Fertilizer and crop management strategies are developed in order to reduce N application rates and N balance surpluses. The objectives of this thesis are:

i. to evaluate the effect of the current N fertilization practice in the rice-wheat double cropping system in Jiangsu Province, China on mineral N dynamics in the soil, NUE and potential N losses,

ii. to develop optimized fertilizer management strategies as well as agronomic practices for the rice-wheat double cropping system in Jiangsu and adjacent provinces and thus to increase NUE and mitigate the environmental N loss potential,

iii. to investigate the effect of the combined application of urea and the nitrification inhibitor DCD in a rice-wheat double cropping system on grain yield, NUE and potential N losses.

Finally, this thesis should contribute to a better understanding of the impact of the present N fertilization practices of Chinese small-scale farmers in the rice-wheat double crop rotation and to point out opportunities for an improved N fertilization and crop management.

2. Nitrogen management in a rice-wheat system in the Taihu Region: Recommendations based on field experiments and surveys[1] – Field experiments in Yixing County

Abstract

Excessive use of mineral nitrogen (N) fertilizer has been a common practice in the high-yielding rice-wheat double-cropping system in the Taihu Region of southeastern China. As a consequence of high N balance surpluses and low N use efficiencies (NUEs), nitrogen losses to water bodies and to the atmosphere are high. Field experiments on five replicate farmers' field sites were conducted in southern Jiangsu Province over three consecutive rice-wheat double-crop rotations with three different N fertilization treatments (`conventional´ (farmers' practice), `reduced´ (by 23 % for rice and 32 % for wheat) and zero N application). A parallel survey was carried out involving 43 farmers' households, in order to calculate standard gross margins (SGM) and to conduct an environmental assessment of the rice-wheat farming system in the Taihu Region. The results of the field experiment showed that a distinct reduction in fertilizer N application rates to summer rice and winter wheat crops is possible without significant decrease in mean grain yields. Mean grain yields for the entire double-crop rotation were 14.7 Mg ha^{-1} yr^{-1} under the conventional N fertilization practice and 14.1 Mg ha^{-1} yr^{-1} under reduced N fertilization. A significant increase in NUEs could be achieved in most years and crops under reduced N fertilization compared to farmers' practice, and N balance surpluses were significantly decreased from 142 kg N ha^{-1} to less than 60 kg N ha^{-1} yr^{-1} under the reduced N fertilization regime. The residual mineral N contents in the soil profiles after winter wheat harvest showed a decreasing tendency over time with a reduction of N fertilization. Mineral N contents in fertilized fields were significantly higher than on the zero N plots. Concentrations of NH_4^+-N in soil extracts from the puddled layer during the summer rice in 2010 showed significant differences between the two N fertilization treatments and the zero N plots. Results of the agro-economic survey showed that production of rice was 50 % more profitable than that of wheat, and that fertilizer costs made up less than 20 % in the rice season, but almost 50 % of the total production costs during the wheat season. It can be concluded that N losses to the environment can be efficiently decreased by reducing the overall N fertilization rates without any risk of decline in grain yield and related income for farmers. Based on the field experiments and investigations, a reduction in N fertilizer application rates by 15-25 % for summer rice and by 20-25 % for winter wheat, compared to present levels is recommended.

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2.1. Introduction

Agriculture in the Tai Lake (Taihu) Region in southeastern China has a long-standing history of rice (*Oryza sativa* L.) cultivation of about 7,000 years (Smith 1995). Irrigated summer rice has been grown in a double-cropping system with winter wheat (*Triticum aestivum* L.) since 1,000 AD with rice as the main crop (Ellis and Wang 1997). Traditional agricultural practices were characterized by complex crop rotations, also including mulberry cultivation and fish ponds, and an almost complete recycling of organic materials as fertilizers to the field. Soil fertility had been maintained for thousands of years and provided stable crop yields at a moderate level (Yang 2006). However, due to a growing population in China, the introduction of new high-yielding varieties and mineral nitrogen (N) fertilizers since the late 1960s and the overall importance of food security, a rapid change in agricultural practices occurred. Over-application of N fertilizer became a common practice and, with the exception of open field vegetables, the application of organic fertilizers to field crops was almost completely abandoned (Gao et al. 2006; Yang 2006; Zhu and Chen 2002). In the part of the Taihu Region belonging to southern Jiangsu Province, mineral N inputs to summer rice were about 280 to 360 kg N ha^{-1} in the mid-late 1990s, those to winter wheat 185 to 285 kg N ha^{-1} (Richter and Roelcke 2000; Roelcke et al. 2004). The resulting mean annual N balance surpluses for summer rice-winter wheat double-cropping systems at two different locations were very high, ranging from 217 to 335 kg N ha^{-1} yr^{-1} (Richter and Roelcke 2000). Nitrogen inputs to summer rice in southern Jiangsu Province have decreased slightly since about 2001 to around 240 to 280 kg N ha^{-1} yr^{-1} in the late 2000s (Li et al. 2010; Qiao et al. 2012) and those to winter wheat have also begun decreasing in the early 2000s (Roelcke et al. 2004). Yet, total annual mineral N fertilizer use currently still exceeds 500 kg N ha^{-1} yr^{-1} for one double-crop rotation.

This high nutrient input in combination with improper timing of N application and a low recovery of fertilizer N by the plants have led to high N surpluses and high losses of reactive N to the environment. In a lysimeter study by Ju et al. (2009) at a research station in Changshu, southern Jiangsu Province, fertilizer N recovery efficiencies amounted to 29.6 % for rice and 34.5 % for wheat, and total N losses of up to 329 kg N ha^{-1} yr^{-1} were reported for one double-crop rotation under farmers´ fertilization practices in the early 2000s. Consequently, the Taihu Region is faced with one of the largest net anthropogenic N inputs in China (Han et al. 2014; Ti et al. 2012). High losses of N from agricultural systems have led to eutrophication of Lake Taihu, growth of cyanobacterial blooms (Conley et al. 2009; Paerl et al. 2011; Qin et al. 2007), regularly exceeding the WHO threshold for N concentration in ground- and freshwater bodies (Chen et al. 2010), deterioration of drinking water quality (Qin et al. 2010) as well as increased atmospheric N depositions (Hayashi and Yan 2010; Luo et al. 2007). An enhanced N deposition in terrestrial and aquatic ecosystems of currently about 21.1 kg N ha^{-1} yr^{-1} , as it was recently reported for China (Liu et al. 2013b), has wide implications for human and ecosystem health, the greenhouse gas emissions and biological diversity (Bleeker et al. 2011; Matson et al. 2002; Sutton et al. 2011; Townsend et al. 2003). Moreover, recent studies have shown that the potential of greenhouse gas emissions associated with agricultural N addition in the lower reaches of the Yangtze River is among the highest in China (Tian et al. 2012) and that anthropogenic soil acidification driven by N fertilization has been significantly increased in the rice-wheat double-cropping system since the 1980s (Guo et al. 2010).

The main loss pathways of fertilizer N during the summer rice growing season are ammonia (NH_3) volatilization and denitrification. Direct measurements of NH_3 volatilization during the rice growth period in the Taihu Region under conventional fertilization practice ranged from 76 kg N ha^{-1} (Zhao et al. 2012b) and 70 kg N ha^{-1} (Yang et al. 2013) to somewhat lower values found by Lin et al. (2007) reporting total NH_3 losses of 50 kg N ha^{-1} with a fertilizer N application rate of 300 kg N ha^{-1}, and by (Li et al. 2008) who measured NH_3 losses up to 32 kg N ha^{-1} in fields with a zero-drainage water management at an application rate of 270 kg N ha^{-1}. Ju et al. (2009) reported apparent denitrification losses of 36 % of applied N to rice, while Zhao et al. (2012b) estimated mean denitrification losses of 79 kg N ha^{-1} or 22.3 % of the applied N during the rice growing season (both calculated by difference-method). Denitrification is promoted by the flooding of the fields after the wheat harvest in preparation for the subsequent rice crop, by draining the fields for mid-season aeration, and before rice harvest (Fan et al. 2007; Zhao et al. 2009). In contrast, denitrification during the wheat growing season occurs mainly due to wet soil conditions, high temperatures during the spring vegetation period and relatively high carbon (C) contents of the soils in the Taihu Region, and account for 44 % of applied N (Ju et al. 2009). Besides denitrification, nitrate (NO_3^--N) leaching and runoff is another major N loss pathway during the winter wheat growing season of Taihu Region. Zhao et al. (2012a) reported N losses through runoff and leaching from paddy soils of 50 kg N ha^{-1} during the wheat growth period. According to Tian et al. (2007) N losses through runoff and leaching for the whole rice-wheat double-crop rotation ranged from 14 to 48 kg N ha^{-1} yr^{-1}, while in a study by Ma (1997) they ranged between 10 and 34 kg N ha^{-1} yr^{-1} and Zhao et al. (2012a) showed that these losses can be as high as 70 kg N ha^{-1} yr^{-1}.

At present, N fertilization recommendations for the Taihu Region and Jiangsu Province are mostly based on exact field experiments on research stations or in well-managed farmers´ experimental field plots, subdivided into subplots that represent different fertilizer treatments. Summarizing results of exact field experiments on farmers´ field sites in the Taihu Region, Ju et al. (2009) found no increase in rice and wheat grain yields for N fertilization rates higher than the recommended ‘optimum N fertilization’, given as 200 kg N ha^{-1} for rice and 153 kg N ha^{-1} for wheat. Xia and Yan (2012) recommended N rates of 190 to 213 kg N ha^{-1} for summer rice in the Taihu Region as optimum rates from an economic and ecological point of view. The latter results were obtained using an economic evaluation model with data from several field experiments around Lake Taihu. Recommendations for N fertilizer application for winter wheat in the Taihu Region have been given by Liang et al. (2008). Based on their field trials on two research stations in the Taihu Region, the ecologically optimum N rate ranged from 120 to 180 kg N ha^{-1}.

Two similar three-year on-farm field studies were carried out in Jiangsu Province from 2008 to 2011, in southern (Taihu region), and northern Jiangsu, respectively. Only the Taihu Region study is presented here; results from N Jiangsu will be presented separately. The objectives of the present study are to (1) derive optimized N fertilization levels for a summer rice-winter wheat double-crop rotation in the Taihu Region in southern Jiangsu Province on farmers´ field sites rather than in exact field experiments, based on farmers’ current N application rates and using a newly-bred rice variety, and thus to (2) increase N use efficiencies, (3) quantify apparent N losses from the rice-wheat system by balance calculations on a plot level, (4) monitor mineral N contents under different N fertilization schemes and finally, to (5) assess the standard gross margin of the rice-wheat system as well as the economic consequences of a reduced N fertilization practice. Improved recommendations for N fertilization are derived on the basis of our results.

2.2. Material and Methods

2.2.1. Location

The experimental site was located in the eastern area of the Taihu basin in Dapu Township (31°17'N, 119°53'E), Yixing County, southern Jiangsu Province, China. This area is characterized by a subtropical climate with a mean annual temperature of 16.3°C and an average annual rainfall of 1,100–1,200 mm, with nearly two thirds of precipitation concentrated during the summer rice growing season from July to October. The altitude was about 5 m above mean sea level, the depth of the groundwater table was 3 m.

The soil of the area was a typical paddy soil, developed in lacustrine deposits under long-term rice cultivation. It was classified as a Hydragric Anthrosol (IUSS Working Group WRB 2007) and as a *huang ni tu* in the Chinese classification system (Xu et al. 1980), with a silt loam texture (>80 % silt) throughout the 0-0.9 m profile (Table 2.1). The soil was free of carbonates and slightly acid in the puddled horizon (0-17 cm). Soil samples were collected separately on five adjacent farmers´ field plots from 0-0.2, 0.2-0.6 and 0.6-0.9 m depth before the onset of the experiment. Samples were air-dried at room temperature, passed through a 2-mm sieve and analyzed for chemical and physical soil parameters described in Table 2.1.

Table 2.1: Mean soil parameters of the experimental fields in Yixing.

Depth (cm)	**pH** (H_2O)	**$CaCO_3$** (%)	**SOC** (%)	**N_{tot}** (%)	**Av. K** (mg kg^{-1})	**Av. P** (mg kg^{-1})	**Sand**[a] (%)	**Silt** (%)	**Clay** (%)
0-20	5.4	n.d.	1.7	0.2	47.4	12.9	0.7	82.9	16.4
20-60	7.6	n.d.	0.4	0.7	37.0	3.3	1.2	84.2	14.9
60-90	7.4	n.d.	0.2	0.05	41.5	3.4	2.0	86.0	12.0

[a] Sand: 2-0.063 mm; Silt: 0.063-0.002 mm; Clay: < 0.002 mm

The main field crops include irrigated summer rice from late June to late October or early November and upland winter wheat or oilseed rape (*Brassica napus* L.) from November to the end of May in a double-crop rotation. Winter wheat is of less economic importance due to the poor varieties grown and because of the wet soil conditions resulting in relatively low grain yields and poor grain quality. There is also an increase in cultivation of open-field vegetables covered by plastic mulch and in plastic greenhouses during the winter cropping season in the recent years.

2.2.2. Experimental design

The field experiment comprised three consecutive double-crop rotations and started in November 2008 with the winter wheat (WW). It was concluded after the third summer rice crop (SR) in early November 2011. The experiment was established on five farmers´ field plots and managed by the local farmers. It was organized in a split-plot design with five replicates following the so-called '3 + x' approach with two different N fertilization treatments as the main factor and a zero N treatment, as well as an agronomical ('x') treatment cross-wise within each fertilization treatment at the sub-plot level. No replicates were established on the same site; instead, the different field plots were treated as replicates. Nitrogen fertilization treatments were 'conventional' (CN) and 'reduced' (RN) N fertilization. Nitrogen-omission plots (zero N) were integrated into the conventionally fertilized plots as rotating microplots, which were shifted after each completed double-crop rotation. As 'x'-treatment, the green manure Chinese Milk Vetch (*Astragalus sinicus* L.) was sown during winter periods on half of the N fertilized plots. This 'x'-treatment was established during the last two winter wheat seasons only and is therefore not further considered in this paper. Plot sizes were 550 m^2 for CN, 1,100 m^2 for RN and 40 m^2 for zero N. The plots were separated by ridges.

The newly-bred rice variety *zhèn dào 10#* was used in all three rice seasons. It was directly sown into the previously puddled and levelled fields at a mean seeding rate of 260 kg seeds ha^{-1} on 16 June 2009, 20 June 2010 and 15 June 2011, respectively. Plant protection measures, irrigation and mid-term aeration were carried out by local farmers according to their local practice. Basal fertilizer was uniformly broadcast by hand as NPK compound fertilizer before sowing and incorporated into the topsoil (0-17 cm) with a flat cultivator. Top-dressing of mineral N fertilizer was carried out in three split applications, with urea applied directly into the ponded water. All zero N plots received a uniform application of 50 kg P ha^{-1} (as single superphosphate) and 50 kg K ha^{-1} as potassium chloride (KCl) before sowing, and 50 kg K ha^{-1} at panicle initiation stage. Details on fertilization rates and dates are given in Table 2.2. Nitrogen fertilization was reduced by 11 % in CN and by 18 % in RN from the second rice crop onwards, as an adaptation to the new rice variety. Rice was harvested with a combined harvester on 31 October 2009, 9 November 2010 and 11 November 2011, respectively.

Table 2.2: Nitrogen fertilizer application rates in kg N ha^{-1} and dates of fertilizer application of summer rice crops 2009 to 2011 in Yixing.

Year	**Treatment**[a]	**Basal fertilization**		**Early tillering**		**Max. tillering**		**Panicle initiation**		**Total**
2009	CN	50	06/16	50	07/01	50	07/16	120	08/01	270
	RN	50	"	35	"	35	"	100	"	220
2010	CN	50	06/20	60	07/05	30	07/26	100	08/08	240
	RN	50	"	50	"	0	"	80	"	180
2011	CN	50	06/15	60	06/30	30	07/14	100	07/31	240
	RN	50	"	50	"	0	"	80	"	180

[a] CN: conventional N fertilization practice (farmers´ practice); RN: reduced N fertilization

Before sowing of the winter wheat in November, rice straw was removed from the fields, stubbles were incorporated into the upper 10 cm of the soil by chisel cultivator and shallow drainage ditches were dug lengthwise with a spacing of about 2 m. After field preparation, the wheat cultivar *huai mai 20#* was broadcast by hand at a mean seeding rate of 178 kg seeds ha^{-1} on 16 November 2008, 09 November 2009 and 12 November 2010, respectively. For basal fertilization, N was applied before field preparation as 56 kg ha^{-1} NPK compound fertilizer and mixed uniformly with the topsoil. Additionally, CN received 41 kg N ha^{-1} as ammonium bicarbonate (NH_4HCO_3) fertilizer. Details on fertilizer application are given in Table 2.3. The zero N plots were fertilized separately with 56 kg P ha^{-1} as single superphosphate and 56 kg K ha^{-1} as KCl. According to the local fertilization practice, mineral N fertilizer was top-dressed as urea in two further split applications during tillering and before shooting stage. All fertilizers were evenly broadcast by hand. However, the first top-dressing was missed in the first winter wheat season and was applied before shooting stage instead, while the second top-dressing was then skipped. Winter wheat was harvested on 30 May 2009, 6 June 2010 and 30 May 2011, respectively, by combined harvester, and manually in the small microplots.

Table 2.3: Nitrogen fertilizer application rates in kg N ha^{-1} and dates of fertilizer application of winter wheat crops 2008/09 to 2010/11 in Yixing.

Year	**Treatment**[a]	**Basal fertilization**		**Tillering stage**		**Shooting stage**		**Total**
2008/09	CN	96	11/19	0	-	70	03/08	166
	RN	56	“	0	“	56	“	122
2009/10	CN	97	11/11	70	01/16	53	03/18	220
	RN	56	“	56	“	38	“	150
2010/11	CN	97	11/13	70	01/12	53	02/24	220
	RN	56	“	56	“	38	“	150

[a] CN: conventional N fertilization practice (farmers´ practice); RN: reduced N fertilization

2.2.3. Sampling and analyses

Grain yields were determined by harvesting the whole plot areas and weighing all the grain in parallel to the harvest operation. For determination of moisture content, grain samples were taken directly after harvest and oven-dried at 80°C until constant weight was reached. Grain yields were then adjusted to a standard 14 % moisture content. In order to determine straw yield, yield components and above- ground N uptake, plant samples were taken before harvest at maturity. Sample size was 10 plants of rice and 30 to 50 ears of winter wheat from each plot. Plants were separated into stem, leaves and panicles/ears and subsamples were pre-dried for 1 h at 105°C followed by drying at 80°C for 48 h. After dry weight determination of the plant parts, subsamples were ground for subsequent analyses of N concentration by Elemental analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Hanau, Germany). Above-ground N uptake was calculated by multiplying N concentration with above-ground dry matter production.

Residual mineral N (N_{min} = NO_3^--N + NH_4^+-N) contents in the 0-0.9 m soil profiles were determined directly after harvest of winter wheat and summer rice crops. Additional N_{min} samples were taken during the winter wheat cropping season before each fertilizer application. Four replicate soil samples were taken randomly on each plot from 0-0.2, 0.2-0.6 and 0.6-0.9 m depth and bulked for each depth increment. The field-moist samples were kept cool (4 °C) during transport and storage, homogenized and extracted within one day with 1 *M* KCl by shaking for 1 h in a 1:4 (w/w) soil:solution ratio. The extracts were analyzed for NO_3^--N and NH_4^+-N using a continuous-flow autoanalyzer (SKALAR, San Plus System, Breda, The Netherlands). Actual bulk densities were used for conversion of N_{min} contents on an area basis.

During the summer rice seasons in 2009 and 2010, mud-soil samples were taken only from the waterlogged puddled layer (0-0.2 m) in two–day intervals for up to 10 days following each fertilizer application event for determination of different N species. Soil columns were collected with a plastic tube of 20 cm length and 5 cm in diameter, in order to include both the soil and the soil solution. The wet samples were centrifuged for soil solution analyses and the remaining soil was extracted with 2 *M* KCl solution. The soil solution was analyzed for NO_3^--N, NH_4^+-N and dissolved organic N (DON) and the soil KCl extract was analyzed for NO_3^-- N and NH_4^+-N.

2.2.4. Nitrogen use efficiencies and N response

Nitrogen use efficiencies were calculated based on the difference in N uptake in above-ground biomass and crop yield vs. the amount of nitrogen applied (‘difference method’), as described by Craswell and Godwin (1984). Agronomic indices used include agronomic efficiency (AE_N) and apparent N recovery efficiency (RE_N). Additionally, the partial factor productivity for nitrogen (PFP_N) and the yield response (Y_Δ) to N fertilizer application (N response) were calculated. These indices were calculated using the following equations:

$$AE_N = (Y_N - Y_0) / F_N \qquad (\text{kg kg}^{-1})$$

$$RE_N = (U_N - U_0) / F_N \qquad (\text{kg kg}^{-1})$$

$$PFP_N = Y_N / F_N \qquad (\text{kg kg}^{-1})$$

$$Y_\Delta = Y_N - Y_0 \qquad (\text{Mg ha}^{-1})$$

in which Y_N and Y_0 are the grain yields (Mg ha^{-1}) with and without fertilizer N input, U_N and U_0 are the total N uptake (kg N ha^{-1}) in above-ground biomass at physiological maturity with and without N input, and F_N is the amount of applied N fertilizer (kg N ha^{-1}). The AE_N describes the yield increase per unit fertilizer applied and is the overall efficiency with which N is used by the crop. Uptake efficiency of fertilizer N is expressed by the RE_N. The partial factor productivity of applied N is more important for farmers than the RE_N, as it integrates the use efficiency of both indigenous N and applied N.

2.2.5. Nitrogen balance calculations

Simple soil surface N balances at field plot level were calculated as the difference between N inputs (N from mineral fertilizer application, atmospheric wet and dry deposition, irrigation water and asymbiotic biological N fixation (BNF)) and outputs (N removed with grain and straw) for both crops and both fertilization treatments. The difference between inputs and outputs reveals the N surplus or deficit. The N surplus is an indicator for potential N losses, such as leaching, surface runoff, ammonia volatilization and denitrification plus the N that is stored in the soil profile as mineral N or immobilized in microbial biomass or the soil organic matter (SOM). Nitrogen from atmospheric deposition, irrigation water and BNF were included in the calculation based on literature values for the region, in order to make the balances comparable with those from other experiments.

2.2.6. Agro-economic survey

A semi-quantitative agro-economic survey was carried out involving 43 farmers' households in November 2010. The interviews centered around socio-demographic indicators as well as evaluating the production process on-farm. The whole factor use in the production process was evaluated, respectively labour input per production step, financial expenses for each step and amounts of factors being used. This concentration on the production process was accompanied by an introduction in which socio-demographic data was asked for and the questionnaire was finalized by asking personal opinions about the environmental attitudes and other related questions. Overall this information helped a great deal to determine the spectrum of current fertilization and production practices before a background of high yields, increasing environmental pollution and ongoing societal change in this developed region of the P.R. China. Standard gross margins (SGM) were calculated and environmental impacts were assessed. In this SGM approach the basic assumption was that labour is family-owned and therefore being provided by whoever is present in these small farms. Family labour was therefore not included in the SGM calculations. Alternatively, we also calculated the 'Returns from grain sales minus fertilizer costs' (Roelcke et al. 2004) of both fertilization intensities in WW09/10 and SR10, which may be a more appropriate measure compared to SGM, since all other production parameters were kept identically in our field experiments. Prices for nitrogenous fertilizers and sales prices for wheat and rice grain were requested in the agro-economic survey.

2.2.7. Statistical analyses

Statistical analyses were performed using Origin Pro Software on grain yields, above-ground N uptake, N efficiency indices and N_{min} contents. Student´s t-test was applied when the variance of the mean between both N fertilization treatments was calculated. When comparing means of all three treatments, an ANOVA was performed. Differences were tested for significance using Tukey´s range test.

2.3. Results

2.3.1. Summer rice

Mean grain yields of summer rice with N fertilizer application ranged from 7.5 Mg ha^{-1} in SR09 to 9.8 Mg ha^{-1} in SR11 (Table 2.4). Compared to CN, grain yields under RN were 1 % higher in SR09 and declined by 6 % and 8 % in SR10 and SR11, respectively. However, the yield decline was only significant ($P < 0.05$) in SR11 (0.82 Mg ha^{-1}). The average yield decrease for all three rice crops under RN compared to CN was -0.40 Mg ha^{-1} (4.7 %). Average grain yield of the zero N plots was 6.38 Mg ha^{-1} indicating a very high indigenous N supply and the N response of summer rice crops to fertilizer N application was lowest of all three rice growing seasons in SR09 with a mean yield increase of 0.74 Mg ha^{-1} for CN and RN. The average N response of CN and RN was considerably higher for the rice crop in 2010 and 2011, with mean yield increases of 2.28 and 2.80 Mg ha^{-1} in SR10 and SR11, respectively. Overall mean yield increase due to N application was 2.13 Mg ha^{-1} under CN and 1.73 Mg ha^{-1} under RN.

Table 2.4: Grain yields, N uptake, N response and indices of nitrogen use efficiency for the summer rice seasons 2009 to 2011 in Yixing.

Year	**Treatment**	**Grain yield** (Mg ha^{-1})	**N uptake** (kg N ha^{-1})	**N response** (Mg ha^{-1})	**AE_N** (kg kg^{-1})	**RE_N** (kg kg^{-1})	**PFP_N** (kg kg^{-1})
2009	CN	7.47 ± 0.43 a	241 ± 19 a	0.68 ± 0.43 a	2.5 ± 1.6 a	0.34 ± 0.07 a	27.7 ± 1.6 a
	RN	7.55 ± 0.16 a	234 ± 25 a	0.79 ± 0.16 a	3.4 ± 0.7 a	0.38 ± 0.11 a	34.3 ± 0.7 b
	Zero N	6.79 ± 0.61 b	150 ± 23 b				
2010	CN	7.92 ± 0.45 a	181 ± 15 a	2.51 ± 0.45 a	10.5 ± 1.9 a	0.38 ± 0.06 a	33.0 ± 1.9 a
	RN	7.46 ± 0.50 a	155 ± 19 b	2.05 ± 0.50 a	11.4 ± 2.8 a	0.37 ± 0.10 a	41.4 ± 2.8 b
	Zero N	5.41 ± 0.26 b	89 ± 5 c				
2011	CN	10.15 ± 0.59 a	241 ± 13 a	3.21 ± 0.59 a	13.4 ± 2.4 a	0.49 ± 0.05 a	42.3 ± 2.4 a
	RN	9.33 ± 0.41 b	214 ± 15 b	2.39 ± 0.41 b	13.3 ± 2.3 a	0.50 ± 0.09 a	51.9 ± 2.3 b
	Zero N	6.94 ± 0.58 c	123 ± 12 c				
Mean	CN	8.52 ± 1.30 a	221 ± 33 a	2.13 ± 1.20 a	8.8 ± 5.1 a	0.40 ± 0.09 a	34.3 ± 6.5 a
	RN	8.12 ± 0.96 a	201 ± 39 a	1.73 ± 0.81 a	9.4 ± 4.8 a	0.42 ± 0.11 a	42.5 ± 7.7 b
	Zero N	6.38 ± 0.86 b	121 ± 30 b				

Means followed by different letters were significantly different at $\alpha = 0.05$ according to Tukey´s range test (Grain yield and N uptake) and Student´s t-test (N response, AE_N, RE_N, PFP_N)
AE_N: agronomic efficiency for N fertilizer applied; RE_N: apparent recovery efficiency for N fertilizer applied; PFP_N: partial factor productivity for N fertilizer application.

The average above-ground N uptake for summer rice in Yixing was 221, 201 and 121 kg N ha^{-1} for CN, RN and zero N, respectively (Table 2.4). The decrease in N uptake under RN compared to CN ranged from 7 kg N ha^{-1} in SR09 to 27 kg N ha^{-1} in SR11, with an average decrease by 9 %. Nitrogen uptake on the zero N plots was highest in the first rice season with 150 kg N ha^{-1} and lowest in the second season with 89 kg N ha^{-1}. Nitrogen uptake by rice in 2010 was distinctly lower compared to the other rice growing seasons.

No significant differences in AE_N among the N treatments were observed in the three rice seasons (Table 2.4). The AE_N ranged from 2.5 to 13.4 kg kg^{-1} and only a slight increase by 0.9 kg kg^{-1} could be achieved with a reduced N fertilization rate in the first and second rice season. Mean AE_N of the three rice crops was just slightly higher by 0.5 kg kg^{-1} under RN compared to CN. Similar to the AE_N, the apparent recovery efficiency of fertilizer N applied to the summer rice crops was not significantly increased by a reduced N fertilization scheme (Table 2.4). The RE_N ranged from 0.34 kg kg^{-1} in the first rice growing season to 0.50 kg kg^{-1} in the last season and there were nearly no differences between CN and RN. The mean RE_N for all three rice crops was 0.40 kg kg^{-1} and 0.42 kg kg^{-1} under CN and RN, respectively. In contrast, greater differences among the N treatments were observed in the PFP_N, with significantly ($P < 0.05$) higher values by 24 % on average in all rice growing seasons under RN compared to CN. Mean PFP_N for all rice crops was 34.3 kg kg^{-1} and 42.5 kg kg^{-1} for CN and RN, respectively.

2.3.2. Winter wheat

Yield levels of winter wheat in Yixing were distinctly lower than those of summer rice with mean grain yields for all three wheat seasons of 6.21, 5.96 and 3.62 Mg ha^{-1} for CN, RN and zero N, respectively (Table 2.5). Grain yields of RN compared to CN were 2 % higher in WW08/09 and 3 % lower in WW09/10. A significant decline ($P < 0.05$) occurred only in WW10/11 with 8 % lower grain yields under RN. However, this yield decline occurred at a much higher yield level than usual for winter seasons, due to favorable weather conditions during the last winter wheat season in 2010/11. On average over the three years, grain yield in RN decreased by 4 % (0.25 Mg ha^{-1}) compared to CN. The yield increase of winter wheat in the fertilization treatments was higher compared to rice, with a mean N response of 2.59 and 2.34 Mg ha^{-1} under CN and RN, respectively. However, N response of the last two wheat crops was approximately at the same level as that of the following rice crops.

Nitrogen contents in grain and straw were higher under CN compared to RN in all three winter wheat seasons, although the increase was only significant ($P < 0.05$) for the last winter wheat crop (Table 2.5). Almost no difference in N uptake between these two treatments occurred in the first winter wheat season (WW08/09) where on average 22 % less fertilizer N had been applied compared to the other two seasons and total N uptake was distinctly lower. The average N uptake by winter wheat on the zero N plots was 61 kg N ha^{-1}, and ranged from 47 kg N ha^{-1} in WW08/09 to 82 kg N ha^{-1} in WW10/11. For all treatments, mean N uptake by wheat was significantly lower than by rice.

The agronomical N efficiency increased significantly ($P < 0.05$) under the reduced fertilization regime compared to CN in the first two winter wheat seasons and was only slightly higher (n.s.) in the third crop (Table 2.5). The mean AE_N was significantly higher by 6 kg kg^{-1} than that of rice with 12.9 and 17.4 kg kg^{-1} under CN and RN, respectively. The recovery efficiency of applied fertilizer N by the wheat crop and the partial factor productivity were similar to those of the summer rice crop. Under reduced fertilization, RE_N was significantly ($P < 0.05$) higher than under CN only in

WW08/09, and the mean RE_N for all three wheat crops was 0.37 and 0.44 kg kg^{-1} for CN and RN, respectively. A significant (P < 0.05) increase in PFP_N under RN compared to CN could be observed in all winter wheat seasons, with a mean PFP_N of 30.5 kg kg^{-1} in CN and 43.3 kg kg^{-1} in RN.

Table 2.5: Grain yields, N uptake, N response and indices of nitrogen use efficiency for the winter wheat seasons 2008/09 to 2010/11 in Yixing.

Year	**Treatment**	**Grain yield** (Mg ha^{-1})	**N uptake** (kg N ha^{-1})	**N response** (Mg ha^{-1})	**AE_N** (kg kg^{-1})	**RE_N** (kg kg^{-1})	**PFP_N** (kg kg^{-1})
2008/09	CN	4.63 ± 0.34 a	98 ± 11 a	2.30 ± 0.34 a	13.9 ± 2.0 b	0.31 ± 0.07 b	27.9 ± 2.0 b
	RN	4.71 ± 0.39 a	96 ± 11 a	2.39 ± 0.39 a	21.3 ± 3.5 a	0.44 ± 0.10 a	42.0 ± 3.5 a
	Zero N	2.32 ± 0.60 b	47 ± 16 b				
2009/10	CN	5.58 ± 0.52 a	135 ± 12 a	2.45 ± 0.52 a	11.1 ± 2.4 b	0.37 ± 0.06 a	25.4 ± 2.4 b
	RN	5.43 ± 0.41 a	117 ± 12 a	2.30 ± 0.41 a	15.4 ± 2.7 a	0.43 ± 0.08 a	36.2 ± 2.7 a
	Zero N	3.13 ± 0.12 b	53 ± 1 b				
2010/11	CN	8.43 ± 0.38 a	179 ± 9 a	3.03 ± 0.38 a	13.8 ± 1.7 a	0.44 ± 0.04 a	38.3 ± 1.7 b
	RN	7.73 ± 0.17 b	150 ± 11b	2.33 ± 0.17 b	15.5 ± 1.1 a	0.45 ± 0.07 a	51.5 ± 1.1 a
	Zero N	5.40 ± 0.48 c	82 ± 7 c				
Mean	CN	6.21 ± 1.72 a	137 ± 36 a	2.59 ± 0.50 a	12.9 ± 2.3 a	0.37 ± 0.08 a	30.5 ± 6.1 a
	RN	5.96 ± 1.37 a	121 ± 25 a	2.34 ± 0.32 a	17.4 ± 3.8 a	0.44 ± 0.08 a	43.3 ± 7.0 b
	Zero N	3.62 ± 1.41 b	61 ± 19 b				

Means followed by different letters were significantly different at α = 0.05 according to Tukey´s range test (Grain yield and N uptake) and Student´s t-test (N response, AE_N, RE_N, PFP_N)
AE_N: agronomic efficiency for N fertilizer applied; RE_N: apparent recovery efficiency for N fertilizer applied; PFP_N: partial factor productivity for N fertilizer application.

2.3.3. Mineral N during winter wheat and summer rice

At the onset of the experiment before sowing of winter wheat 2008/09, initial soil mineral N contents in the 0-0.9 m soil profiles on the various sites ranged from 26 to 52 kg N ha^{-1} with 34 kg N ha^{-1} on average (data not shown). Moreover, residual N_{min} contents in the 0-0.9 m soil profiles after summer rice harvest showed no clear differentiation between treatments (Figure 2.1). Mean N_{min} contents for all treatments were 18.2, 41.8 and 21.3 kg N ha^{-1} in 0-0.9 m after the summer rice seasons 2009, 2010 and 2011, respectively. While mineral N in the profile was nearly depleted after the first and the third summer rice crops, a considerable amount of N_{min} remained in the soil after the summer rice season 2010 in all treatments.

Compared to the mean residual N_{min} contents after the summer rice season, mineral N contents after winter wheat harvest were only higher under CN but not under RN and zero N (except after the first wheat growing season). There was no difference between the treatments after the first winter wheat crop but a clear differentiation became apparent after WW09/10 and WW10/11, with highest N_{min} contents in CN and lowest in zero N (Figure 2.1). Significantly (P < 0.05) higher contents of mineral N were only found after WW09/10 under CN.

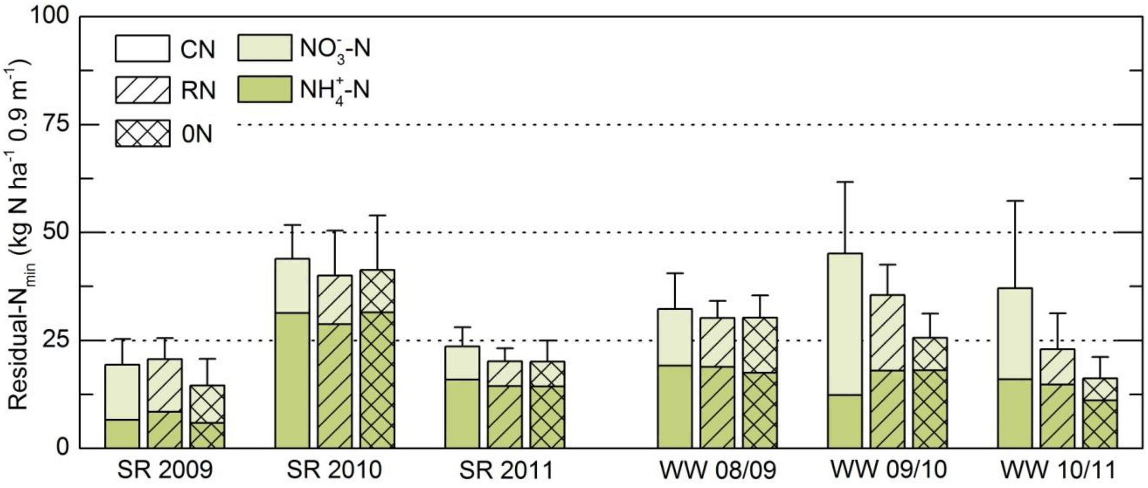

Figure 2.1: Mean residual N_{min} contents (n=5) in 0-0.9 m depth after harvest of summer rice (SR) and winter wheat (WW) crops during the three-year field experiment (2008/09-2011). Error bars present standard deviation of the mean.

Relatively high portions of NH_4^+-N in total residual N_{min} were observed several times, in particular at the end of the rice growing seasons 2010 and 2011, as well as after the winter wheat growing season 2008/09. Higher portions of NO_3^-N were found after the winter wheat growing seasons 2009/10 and 2010/11 in the N fertilization treatments, with significantly higher amounts of nitrate under CN compared to RN.

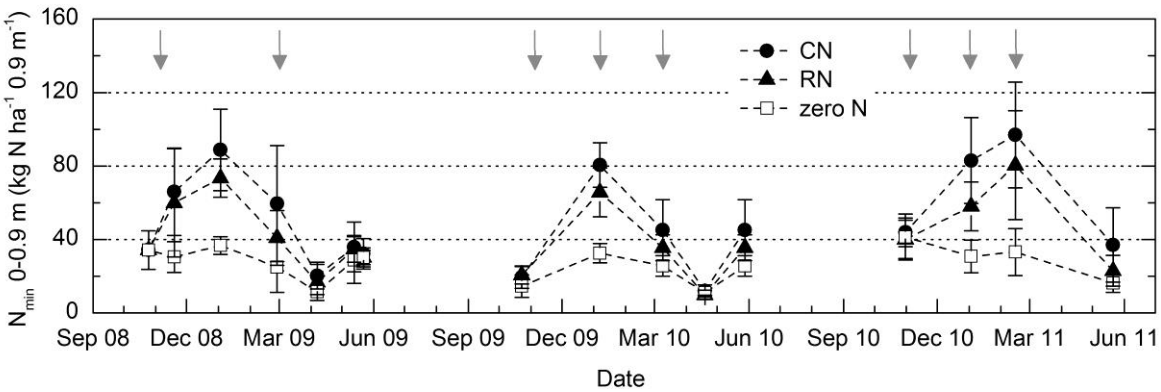

Figure 2.2: Time courses of mean N_{min} contents (n=5) in 0-0.9 m depth, expressed in kg N ha^{-1} under conventional fertilization (CN), reduced fertilization (RN) and zero N during the three winter wheat seasons (2008/09, 2009/10 and 2010/11). Arrows indicate fertilizer N application events. Error bars represent standard deviation of the mean.

The time courses of N_{min} contents in the 0-0.9 m soil profiles during the three winter wheat seasons showed a pronounced effect of N fertilizer application and consistently higher N_{min} contents under CN compared to RN (Figure 2.2), although differences were not significant. Mineral N contents in the fertilized fields were significantly higher ($P < 0.05$) compared to the zero N plots. Contents of N_{min} under CN and RN increased after basal and winter fertilization (N_{min} contents in mid-February ranged from 73 to 88 kg N ha^{-1}) and declined during the spring vegetation period of winter wheat

(February to June). The lowest N_{min} contents during the wheat seasons 2008/09 and 2009/10 were observed in mid-April followed by a slight increase until wheat harvest.

The NH_4^+-N concentrations in soil extracts from the puddled layer during the summer rice growing season in 2010 showed significant (P < 0.05) differences between the two N fertilization treatments and the zero N plots (Figure 2.3a), with high concentrations during the early growth stages and slightly higher concentrations under CN than under RN. However, NH_4^+-N concentrations in the centrifuged soil solutions did not differ between RN and zero N but was significantly (P < 0.05) higher only under CN (Figure 2.3b).

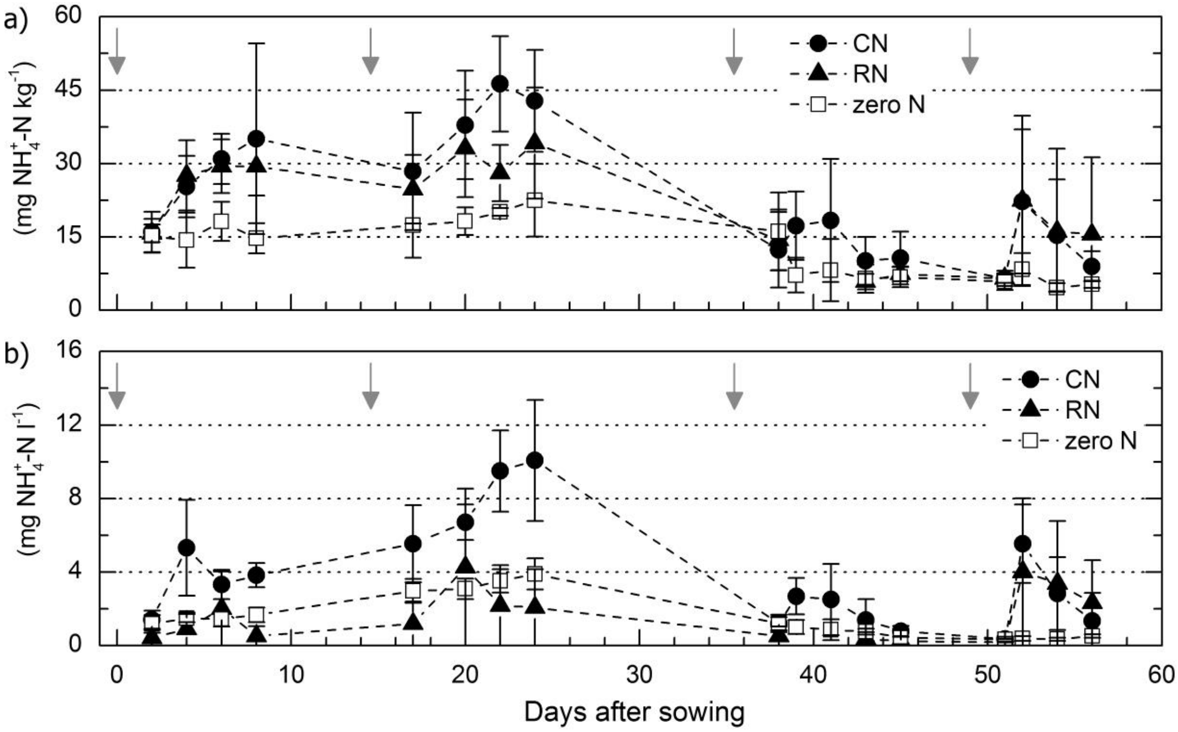

Figure 2.3: Time courses of mean NH_4^+-N contents (n=5) in soil KCl extracts, expressed as mg NH_4^+-N kg^{-1} (a) and in soil solution, expressed as mg NH_4^+-N L^{-1} (b) of puddled layer (0-0.2 m) following conventional fertilization (CN), reduced fertilization (RN) and zero N during the summer rice season 2010. Arrows indicate fertilizer N application events. Error bars represent standard deviation of the mean.

2.3.4. Nitrogen balances

The N balance calculations assumed that most of the rice straw was either removed from the fields or incorporated into the soil and that the N in straw was not prone to losses (Table 2.6). The calculated nitrogen input/output balances on field plot scale basis showed distinct differences between crops and treatments. Total N input and output for the winter wheat crop was generally lower than for the summer rice crop and both N input and output was significantly lower under RN compared to CN (Figure 2.4a). However, the mean N surplus in the winter wheat crop was 25 kg N ha^{-1} higher under CN and 14 kg N ha^{-1} higher under RN than the surplus of rice, due to the considerably lower total N uptake by the wheat crop at the high N fertilization level. Mean N balance surpluses under the reduced N fertilization were 61 %, 56 % and 59 % lower than under CN for rice, wheat and the double-crop rotation, respectively (Table 2.6). Looking at the single years (Figure 2.4b), N surpluses for winter wheat were significantly ($P < 0.001$) reduced under RN compared to CN during all three years. For the summer rice crop, the decrease in N surpluses was not as marked though still significant (P < 0.01-0.05). Compared to the N input with mineral N fertilizer, N inputs via atmospheric deposition, irrigation water and biological N fixation were small. The relative portion of N removed with grain was much higher in wheat than in rice, where nearly half of the above-ground N was present in the crop residues. In contrast, mean absolute amounts of N removed in grain were almost the same for rice and wheat during the three years.

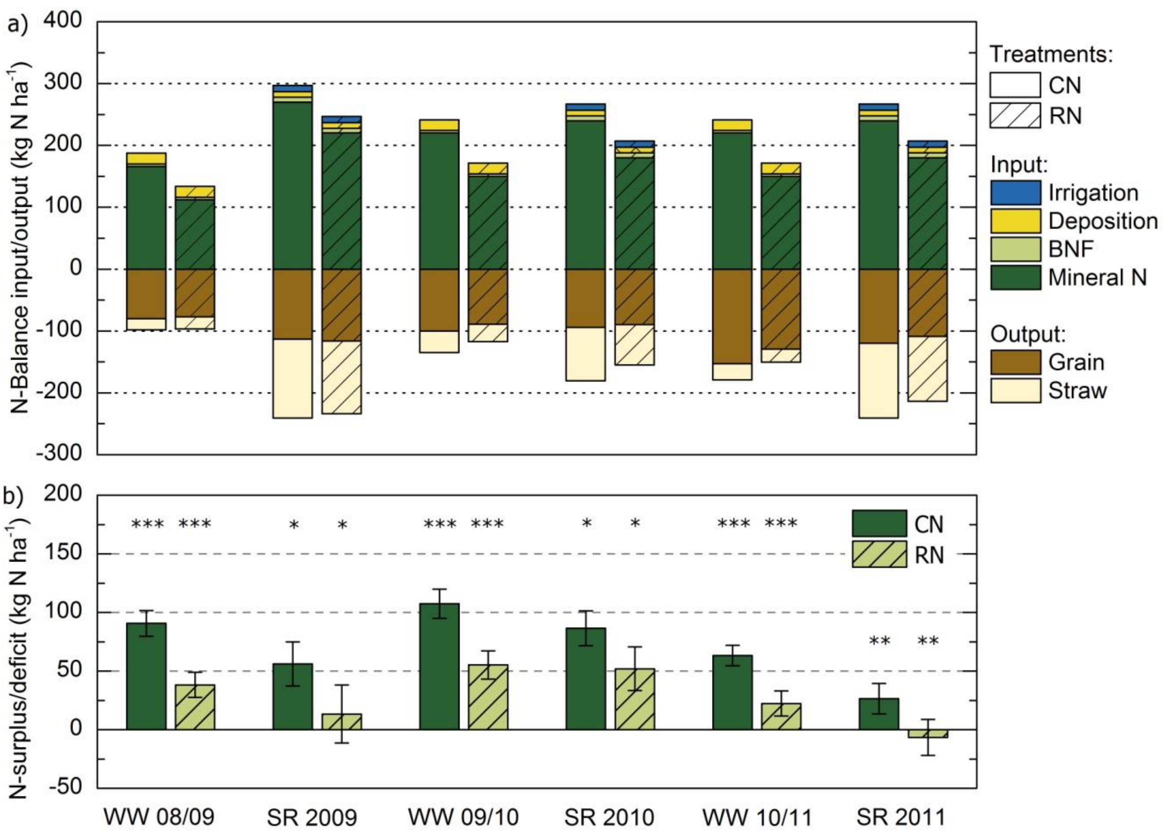

Figure 2.4: Input and output elements in kg N ha^{-1} for N balance calculations on field plot scale basis (a) and mean N balance surpluses/deficits (b) of conventional (CN) and reduced (RN) fertilized treatments during all growing seasons during the three-year field experiment (2008/09-2011) in Yixing. Error bars represent standard deviation of the mean (n=15); *, **, *** significant at 0.05, 0.01 and 0.001 probability levels, respectively.

Table 2.6: Mean N balances (n=15) in kg N ha^{-1} of three consecutive years (2008/09-2011) on field plot scale basis for rice and wheat crops and for the complete double-crop rotation of conventional (CN) and reduced (RN) fertilized treatments in Yixing.

N in-/output balance	Summer rice		Winter wheat		Rice-wheat rotation	
(kg N ha^{-1})	CN	RN	CN	RN	CN	RN
Grain yields (Mg ha^{-1})	8.52 ± 1.30	8.12 ± 0.96	6.21 ± 1.72	5.96 ± 1.37	14.73 ± 2.97	14.07 ± 2.28
Input	**281 ± 15** ***	**225 ± 20** ***	**223 ± 26** ***	**159 ± 18** ***	**504 ± 12** ***	**383 ± 1** ***
Mineral N fertilizer	250 ± 15	193 ± 20	202 ± 26	137 ± 18	452 ± 12	331 ± 1
Atmosph. N dep.[a]	12	12	16	16	28	28
N in irrigation water[b]	12	12	-	-	12	12
Biological N fixation[c]	8	8	5	5	13	13
Output	**221 ± 33**	**201 ± 39**	**137 ± 36**	**121 ± 25**	**358 ± 49** *	**322 ± 43** *
N in grain	109 ± 14	105 ± 15	111 ± 33	99 ± 25	220 ± 40	203 ± 28
N in straw	112 ± 22	96 ± 25	26 ± 8	23 ± 5	138 ± 18	119 ± 21
N balance surplus grain + straw removed	**61 ± 29** **	**24 ± 31** **	**86 ± 21** ***	**37 ± 17** ***	**146 ± 47** ***	**60 ± 43** ***
Only grain removed	172 ± 18 ***	120 ± 17 ***	112 ± 24 ***	60 ± 19 ***	284 ± 35 ***	179 ± 28 ***

[a] Zhai et al. (2009),
[b] Zhao et al. (2012c),
[c] Roger and Ladha (1992a); Ledgard and Giller (1995),
*, **, *** significant difference between treatments within crops and double-crop rotation at 0.05, 0.01 and 0.001 probability levels, respectively.

2.3.5. Agro-economic survey

Results of the farmers' survey showed that, although total production costs for rice production in Yixing were higher than for wheat, rice production was 50 % more profitable than wheat (Table 2.7). Fertilizer costs made up almost 50 % of the total production costs in wheat production, but less than 20 % in rice production (Figure 2.5). This is a strong indicator for the more labour intensive and more capital extensive character of rice production compared to wheat and the high importance of available labour on-farm for the rice production process. The calculation of the 'Returns from grain sales minus fertilizer costs' comparing CN and RN for WW09/10 and SR10, respectively, showed only slight differences between the two fertilizer treatments. While for WW09/10 the 'Returns from grain sales minus fertilizer costs' were slightly higher by 5 RMB mu^{-1} under RN compared to CN, the opposite was the case for SR10, with 58 RMB mu^{-1} higher returns under CN (data not shown). Furthermore, we found that although most farmers interviewed were worried about the environment, they so far were not reflecting that probably they were a source of the problem. Such behavior is well known in the western world as the 'Not in my backyard' (NIMBY) concept, insofar as the farmers saw the problem in their neighbours' behavior rather than in their own. Adding up to this was a shared attitude that the 'government' should avoid to increase prices for fertilizers and other production factors. In line with economic theories as well as expectations most farmers were worried about sharp increases in fertilizer prices as this would endanger their household income to a large extent. Overall, we therefore found that the farmers did not neglect the fact that they were using too much fertilizers; however, they substituted by this the risk of a harvest failure and paid a premium towards higher yields.

Table 2.7: Results of agro-economic household survey in Yixing (43 households in Dapu Township, Nov. 2010).

	Mean total production costs (RMB[a] mu^{-1} [b])	**Mean fertilizer costs** (RMB mu^{-1})	**Relative fertilizer costs** (% of production costs)	**Mean returns** (RMB mu^{-1})	**Mean SGM** (RMB mu^{-1})
Rice production	473.08	79.01	16.7	1106.75	633.67
Wheat production	166.62	80.07	48.1	579.14	409.96
Total					**1043.63**

[a] RMB = Chinese Yuan. 1 US $ = approx. 6.17 RMB (April 2014);
[b] 1 mu = 1/15 ha = 666.67 m^2

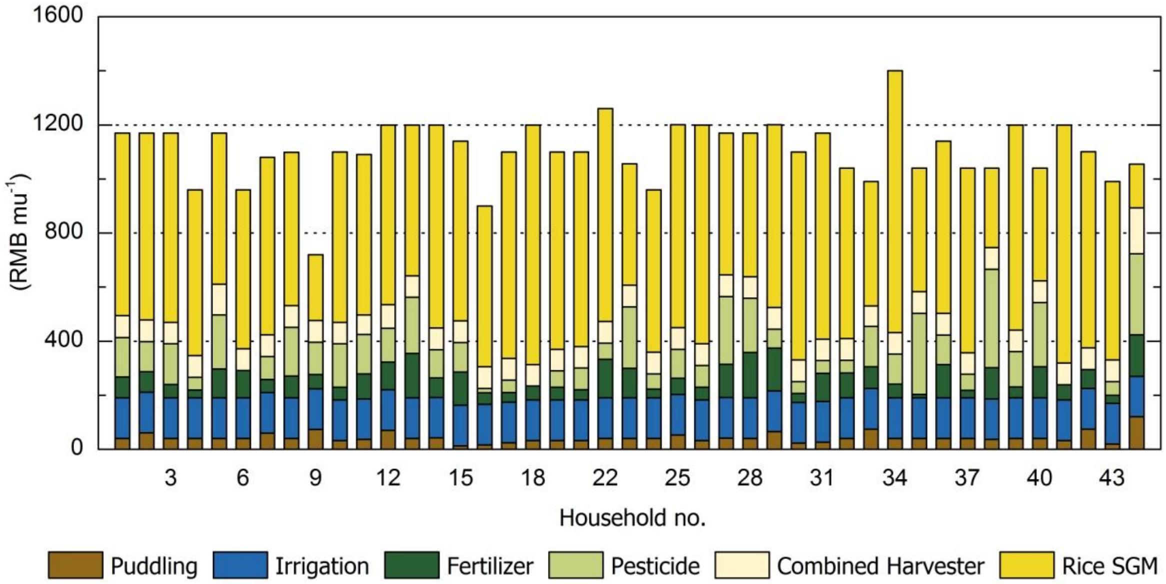

Figure 2.5: Production costs and standard gross margins (SGM) of rice production in Dapu Township, Yixing County, based on a semi-quantitative farmers' survey (43 households) carried out in November 2010. RMB = Chinese Yuan. One US $ approx. 6.17 Chinese Yuan (April 2014). One mu = 666.67 m^2.

2.4. Discussion

2.4.1. Grain yield and N response

On average of the three consecutive rice-wheat rotations no significant decline in grain yield with mean reduction of N fertilizer application rates by 23 % for rice and by 32 % for wheat compared to conventional fertilizer application rates could be observed. However, after a marginal grain yield increase under RN compared to CN in the first rice and wheat seasons, grain yields tended to decrease slightly over the next two growing seasons under reduced N fertilization regime. Disproportionately high grain yields were observed in the third year of the field experiment for both rice and wheat, due to a high amount of sunshine hours during the rice growing season and drier weather conditions during the wheat growing season, which were more favorable for crop growth and yield formation. The average grain yield of summer rice under the farmers´ N fertilization practice was on a comparable level with that reported by Peng et al. (2006) and Qiao et al. (2013) for transplanted rice in Jiangsu Province, and for directly seeded rice in the Taihu Region by Li et al. (2010). Somewhat lower grain yields for directly seeded rice in an exact field trial located on neighboring sites in Yixing were reported by Zhao et al. (2012b), where rice yields on a dry weight basis ranged from 5.4 to 6.5 Mg ha^{-1} with N fertilizer application rates of 300 kg N ha^{-1}. Grain yields of winter wheat in the same experiment fertilized with 200 kg N ha^{-1} ranged from 4.3 to 4.7 Mg ha^{-1}. The average winter wheat grain yield in our study was similar to results from field experiments on two research stations in southern Jiangsu Province, where the mean yield was 6.0 Mg ha^{-1} with a fertilizer application rate of 225 kg N ha^{-1} (Wang et al. 2004).

Yield response to fertilizer N application has gradually been decreasing in Chinese cropland due to an upper limit of yield levels on the one hand and continuously increasing fertilizer application rates on the other hand (Chai et al. 2013). The average yield response to N fertilizer application in China under common fertilization practice is around 1.5 Mg ha^{-1} for rice (Peng et al. 2010) and slightly higher for wheat with 1.7 Mg ha^{-1} (Chuan et al. 2013). However, Peng et al. (2006) reported higher yield responses for rice in Jiangsu Province, which ranged from 2.2 to 3.0 Mg ha^{-1} and were comparable with the mean yield response in our last two rice growing seasons (2.9 Mg ha^{-1}).

Low yield responses to fertilizer N application are caused by the high indigenous N supply in intensive rice growing areas of China like the Taihu Region (Peng et al. 2006). Nitrogen sources other than from fertilizers originate from irrigation water that may contain high amounts of N, from wet and dry atmospheric N deposition and, especially during the rice season in the zero N plots, from non-symbiotic biological N fixation through cyanobacteria. A detailed estimation of N inputs in the study location was made by Zhao et al. (2012b) who reported N inputs of 11.8 kg N ha^{-1} from irrigation water, 31 kg N ha^{-1} from atmospheric deposition and 60 kg N ha^{-1} from biological N_2 fixation. However, reported N inputs in the Taihu Region with irrigation water ranged from 5.1 kg N ha^{-1} yr^{-1} (Zhu 1997b) to 56 kg N ha^{-1} yr^{-1} (Ju et al. 2009; Xie et al. 2008), and asymbiotic N_2 fixation by blue-green algae in rice fields with broadcasted urea can be as low as 8 kg N ha^{-1} $crop^{-1}$ (Roger and Ladha 1992b). These additional N sources have not been considered up to now by Chinese rice farmers in their fertilization concepts.

2.4.2. Nitrogen uptake and N use efficiencies

Total above-ground N uptake of more than 240 kg N ha^{-1} under CN in the rice growing seasons 2009 and 2011 were in the same range as the mean N uptake of rice in farmers´ field sites in Jiangsu Province reported by Peng et al. (2006), where N uptake was generally higher compared to other rice growing regions of China. Despite the high N uptake, the mean RE_N was only about 0.41 kg kg^{-1} due to high N uptake by the rice crop on the zero N plots, and only a slight increase of RE_N was observed under RN, due to the higher N uptake by summer rice under CN compared to RN. However, this RE_N was higher than values previously published by Zhu (1997a) who estimated a RE_N for agricultural production in China of 0.30 to 0.35 kg kg^{-1} and by Cassman et al. (2002) who reported a mean RE_N for irrigated rice in China of 0.31 kg kg^{-1}. A more recent study on N efficiency of irrigated rice in China reported a RE_N of up to 0.40 kg kg^{-1} (Qiao et al. 2012), which was similar to our findings and indicated a slight increase in N recovery efficiency in the last decade. Nevertheless, most published values for RE_N for rice in China are still lower than the RE_N in well-managed agricultural systems that range from 0.50 to 0.80 kg kg^{-1} (Cassman et al. 1993; Dobermann 2007; Peng and Cassman 1998). Similarly to the RE_N, despite the high grain yields of summer rice, the mean AE_N in our study was only 9.1 kg kg^{-1} and only slightly higher values were observed under RN compared to CN. The low AE_N values were caused by the very high grain yields of the rice crop on the zero N plots, leading to low yield response of summer rice to fertilizer N. Comparably low AE_N values for summer rice in Jiangsu Province were reported by Wang et al. (2001) and Peng et al. (2006), indicating that there was no improvement in AE_N in the recent years. In contrast to RE_N and AE_N, the PFP_N from applied N fertilizer was significantly increased by 24 % under RN compared to CN, which may indicate an increased utilization of indigenous N in the 'reduced' fertilized treatments. As the PFP_N is the ratio of total grain output to applied N inputs, it reflects the incremental increase in yield that results from N application and the ability to utilize indigenous N resources from the soil-floodwater system (Cassman and Pingali 1995).

Above-ground N uptake by winter wheat was significantly lower compared to summer rice despite a sufficient nutrient supply, which clearly shows the limited N uptake ability of grown wheat varieties in the Taihu Region. Low N uptake of winter wheat in southern Jiangsu Province was also reported by others (Jing et al. 2009; Zhao et al. 2012b). Despite the low N uptake in the N fertilized treatments, the mean RE_N of winter wheat (0.39 kg kg^{-1}) was similar to that of summer rice, due to low N uptake by wheat on the zero N plots. Only a slight increase in RE_N was observed under RN, again due to the higher N uptake by winter wheat under CN compared to RN. Although the average AE_N in our study for winter wheat (15.1 kg kg^{-1}), was higher than the mean AE_N for winter wheat in China (9.4 kg kg^{-1}) reported by Chuan et al. (2013), it is still lower than the world average AE_N for cereal crop production of 18 kg kg^{-1} calculated by Ladha et al. (2005). Generally, above-ground N uptake, RE_N and AE_N increased only slightly under RN compared to CN. However, similarly to rice, a significant increase by 42 % in PFP_N of winter wheat was observed under RN.

2.4.3. Residual mineral nitrogen

The residual N_{min} contents after the summer rice seasons 2009 to 2011 were in the same range as the initial ones found at the onset of the experiments. Mineral N contents after summer rice were not affected by N fertilization, but by differences in crop N uptake between years. As the last N fertilization event had been three months before rice harvest, most of the residual N_{min} derived rather from mineralization of soil organic N after drainage of the fields a few weeks before crop harvest than from applied N fertilizer. An almost total depletion of soil N_{min} profiles, as described by Roelcke et al. (2002; 2004) and Fan et al. (2005), was observed at the end of the summer rice seasons in 2009 and 2011 and a carry-over of residual N_{min} from rice to the subsequent wheat was limited. However, due to distinctly lower crop N uptake and consequently higher N balance surplus in 2010 (Figure 2.4a, Figure 2.4b), between 40 and 50 kg N ha^{-1} were still left in the 0-0.9 m soil profiles after SR10. This mineral N accumulation might have been favoured by high air temperatures after final drainage of the fields one month before harvest.

Residual N_{min} contents in 0-0.9 m after the first winter wheat season were at the same level for all treatments, which was likely caused by the significantly lower amounts of fertilizer N applied to CN and RN compared to the other seasons. More differentiation between the fertilization treatments was observed after winter wheat seasons 2009/10 and 2010/11, with clearly higher N_{min} contents under CN compared to RN and zero N. Residual mineral N at wheat harvest may have been derived from fertilizers applied during winter (see Table 2.3) as well as from soil organic N mineralized during the spring vegetation phase of winter wheat (between shooting stage and harvest, late February to June), and in particular after flowering stage in mid-April, when mineralization rates are high and N uptake is low. Other reasons for the differences in residual N_{min} contents between the winter wheat growing seasons may have been the unknown previous fertilization history of the field sites, as well as a possible carry-over effect of N in organic forms, making the differences in the residual N_{min} in soil profiles under the different treatments more pronounced as the field experiment progressed. Generally, part of fertilizer N is transformed to microbial N or dissolved organic N (Reichardt et al. 2000) during the rice-growing season, which has not been looked at here. Residual N_{min} contents, and nitrate-N in particular, at wheat harvest are subject to leaching and/or transformation losses (denitrification) during the flooding of the field for the subsequent rice crop under high temperatures in summer (Ju et al. 2004; Roelcke et al. 2002), and should therefore be restricted to a minimum.

2.4.4. Nitrogen balances of rice-wheat rotation

Mean N balance surpluses were higher for winter wheat than for summer rice, both under CN and RN, if grain and straw were removed. The N surpluses significantly decreased under the ‘reduced’ N fertilization practice without negatively affecting yield levels of the cropping system significantly. Overall, the mean N surplus for the whole double-crop rotation was diminished by 86 kg N ha^{-1} yr^{-1} to 60 kg N ha^{-1} yr^{-1} under the ‘reduced’ N fertilization regime compared to the farmers´ practice (146 kg N ha^{-1} yr^{-1}). This considerable decline clearly shows the huge reduction potential for N application in intensive agriculture of the Taihu Region and offers a chance to easily reduce the overall N losses from the rice-wheat double-crop rotation with simple measures. Nitrogen losses are forced by a nitrogen supply in excess, which has been described as the main driving factor for N losses out of agricultural systems (Ladha et al. 2005). Nitrogen surpluses of the rice-wheat rotation in the Taihu Region were considerable lower compared to the maize-wheat double-cropping system of the North China Plain, where recently reported N surpluses for one crop-rotation under farmers´ fertilization practice ranged between 56 and 262 kg N ha^{-1} yr^{-1} (e.g., Hartmann et al. 2014).

However, a closer look at the output side of the N balance calculations shows that especially for summer rice nearly half of the N is removed with the crop residues if residues are not retained on the field. Time limitations in the double-cropping system force farmers to harvest the crop before senescence is completed and the N content in the rice straw is thus high (Qiao et al. 2012). Although crop residues were removed from the fields in the present study, it is still a not uncommon practice for farmers in the Taihu Region to burn the cereal straw after harvest on the fields instead of incorporating it into the soil or removing it for other uses (Yang et al. 2008). If rice crop residues were incorporated into the top-soil or mulched onto the field, nearly 100 kg ha^{-1} of organically bound N might be mineralized during the following crop growth seasons and contribute as N source for the subsequent crops. However, rice straw management also effects N_2O emissions during the wheat season. It can either reduce (Ma et al. 2010; Pandey et al. 2012; Zou et al. 2005) or increase (Pathak et al. 2006b) the N_2O emissions. Compared to rice crop residues, the N content of wheat straw is much lower and effects of wheat straw incorporation on crop growth and N losses to the environment are more diverse. Incorporated wheat straw is a strong source of methane (CH_4) emissions under flooded conditions and high temperatures during the subsequent summer rice season (Ma et al. 2008; Ma et al. 2009; Singh et al. 1996; Zou et al. 2005) but seems to be an effective measure for the mitigation of N_2O emissions (Yao et al. 2010). Previous studies have shown that incorporation of wheat straw prior to summer rice may lead to increased NH_3 volatilization losses by 11 kg N ha^{-1}, compared to total NH_3 losses of more than 50 kg N ha^{-1}, or 21 % of fertilizer N applied (Wang et al. 2012). However, for direct seeded rice in the Taihu Region under reduced N fertilization, Xu et al. (2009) documented increased grain yields of rice and better crop performance during grain-filling stage after incorporation of wheat straw prior to summer rice. Generally, only 44 % to 53 % of total annual N inputs to the double-crop rotation were removed by grain under CN and RN, respectively, which is comparable with results from Zhao et al. (2012b).

Comparing the N surpluses for CN in our study (Table 2.6, Figure 2.4b) with those reported by Richter and Roelcke (2000) and Roelcke et al. (2004) for field experiments conducted from 1995 to 1998 at two locations in southern Jiangsu Province, the mean N balance surpluses have been diminished by almost 60 % for rice, and about 30 % for wheat. Compared with the 1990s, grain yields of wheat (Table 2.5) were about 50 % higher, while mean grain yields of rice were almost unchanged. The distinct reduction in N balance surpluses for both crops was mainly due to the lower mineral N fertilizer amounts applied in our field experiment compared to those applied in the mid-late 1990s, combined with higher N uptake rates, in particular by winter wheat. This decline in N surpluses parallel to increased grain yields in the past 10-15 years has confirmed the assumptions and recommendations of the early 2000s, that reductions of the originally very high N application rates were possible without concomitant decreases in grain yields. The currently still existing N balance surpluses ranging from 31 to 91 kg N ha^{-1} for summer rice and from 62 to 106 kg ha^{-1} for winter wheat imply a further reduction of N application rates by 15-25 % for summer rice and by 20-25 % for winter wheat as we currently recommend. The rice-wheat system around Dapu Township close to Lake Taihu is currently 'N-saturated' which is represented by high mineral N concentrations in drainage and irrigation water, fish ponds and other surface waters. The recent changes in nitrogen inputs to cereal crops in Jiangsu Province have also been reflected on a province-wide basis: After having risen constantly for decades, total fertilizer N consumption data and calculated figures for N application per hectare sown area for the year 2010 in Jiangsu were both slightly below their 2005 levels, although the mean grain yield had increased by 6 % from 2005 to 2010 (Ministry of Agriculture 2006; 2011; NPK compound fertilizers with 30% N assumed).

Nitrogen balance calculations are a suitable indicator for potential N emissions to the environment, without giving details on the various loss pathways (gaseous and/or leaching losses), in case that long-term N immobilization can be excluded. These losses, preferably determined through direct measurements, may be summed up separately in a ‘loss balance’ (Richter and Roelcke 2000) and should roughly add up to the N balance surplus. The losses should not, however, be used as an output term of the N balance calculation (e.g., Ju et al. 2009; Zhao et al. 2012b), because the surplus N is the primary cause for environmental implications of N losses. Otherwise, this would imply that the system was somehow almost ‘in balance’ even under very high N surpluses and that any reductions of the very high N inputs would only be very difficult to accomplish.

2.4.5. Agro-economic survey

Farmers in Yixing knew that they were applying too much fertilizers as well as pesticides. This in turn reduced in their understanding the production risks related to weather conditions and other risks. Furthermore, as the household incomes provided by farming were low, we found that a large number of the middle aged generation (between 30 and 50 years old) actually supplemented the farm income by off-farm labour. This in turn proves that farmers are more risk averse than expected and therefore substitute labour by capital (even in labour intensive rice). This can be understood very well, as often farmers are not present at the optimal time to apply fertilizers or spray pesticides. At the moment, there are two different thinkable approaches to reduce factor use in the Yixing farming community. Firstly, to enhance structural change and have more efficient larger scale farms with full-time farmers that can achieve a decent income only from farming. These changes can be accelerated by the rapidly developing off-farm markets, leading to the emergence of cultivated land rental markets (Huang et al. 2012).Or secondly, taking into account that most of the labour on farm today is from the retired generations, make sure that this older generation is better informed and the necessary machinery as well as production process support (training, advisory support, etc) is provided by the government or other institutions. Finally, the results presented in Section 3 and discussed in Section 4 show that experimental sites in a village can be a valuable source of information for farmers. If the advisory services used such an instrument to show and tell farmers how to enhance their production they could easily copy and even perfect such production processes more.

2.4.6. Recommendations on N fertilizer application

As resulting from the field experiments, the N balance calculations as well as from the agro-economic surveys, our study suggests that there is a high potential for the optimization of N fertilizer management in the rice-wheat double-cropping system in the Taihu Region. Generally, around 20 % of fertilizer N can easily be saved during the whole double-crop rotation with an appropriate fertilizer management. Greatest improvements can be made with a reduction of the N fertilizer application rate and the timing of N application. Other aspects, like the type of N fertilizer and the fertilizer placement (Ladha et al. 2005), or agronomic practices such as a reduction in the depth of the ponded water (Jing et al. 2009; Liu et al. 2003; Zou et al. 2005), should be considered as well, but are of less importance for the traditional small scale farming systems of southeastern China. For summer rice crops, it can be deduced from the field experiments and N balance calculations that the reduction potential for N fertilizer application rates without negative effects on grain yields ranges between 15 and 25 % of the current farmers´ practice N rates of around 270 kg N ha^{-1} $crop^{-1}$. A reduction of fertilizer application rates was also necessary because of the newly used rice variety *zhèn dào 10#* that has, in contrast to formerly grown varieties, been bred to be less ‘N tolerant’. It has an improved internal use of N for yield formation and can therefore attain higher yields with less N uptake. We recommend N application rates to summer rice in Yixing between 200 and 230 kg N ha^{-1} (approx. 220 kg N ha^{-1}), depending on yield expectations, and thus slightly higher than the ‘reduced’ treatments of our field experiments. This level was chosen due to the decrease in rice grain yield observed in the third year of experiments under RN compared to CN, albeit at a higher yield level. Moreover, the calculated ‘Returns from grain sales minus fertilizer costs’ for SR10 showed that the reduced N fertilization led to a slight loss of profit and our recommendation is to be seen as a compromise between maximum grain yield security and environmental impact. These figures are comparable with recommendations given by Wang et al. (2004) for transplanted rice in southern Jiangsu Province, who reduced N fertilizer application rates to 225 kg N ha^{-1} and attained similar grain yields as under the farmers´ fertilization practice (300 kg N ha^{-1}) with mean grain yields of 8.1 Mg ha^{-1}. In line with this, an economically optimum N fertilizer application rate for summer rice in the Taihu Region of 227 kg N ha^{-1} was reported by Lin et al. (2007) and no significant differences in grain yield under N fertilizer application rates of 135 to 270 kg N ha^{-1} were observed by Qiao et al. (2012).

A slightly greater reduction potential is given for winter wheat. We recommend a reduction of N fertilizer application rates by 20 to 25 % compared to the current farmers´ practice of around 220 kg N ha^{-1} per crop. This recommended level was again slightly higher than in our ‘reduced’ treatments, due to the decrease in wheat grain yield in the third year. However, the calculated ‘Returns from grain sales minus fertilizer costs’ for WW09/10 showed that there were no large differences in profit between the two N fertilization treatments. The recommended total N application rates of around 170 to 180 kg N ha^{-1} to winter wheat lie in the same range as recently suggested ‘ecological’ N rates to winter wheat in the Taihu Region of 120 to 180 kg N ha^{-1} $crop^{-1}$ (Liang et al. 2008). It should be mentioned, however, that part-time farmers may be carrying out fewer split applications to rice and wheat, thereby increasing the risk of N over-application during the early growing stages and consequently higher N losses.

Besides the total N fertilizer application rate, adequate timing of fertilizer application is another measure for efficient fertilizer management. Chinese small-scale farmers tend to apply large proportions of total N fertilizer as basal fertilizer or in the early vegetative growth stages (Miao et al. 2011; Peng et al. 2010). On our zero N plots, low N uptake by the direct seeded rice crop during the seedling stage and high above-ground N uptake during later stages as well as high grain yields indicated that the soil, irrigation water, etc. can provide significant amounts of indigenous N during the early growth stages. This was also investigated by Li et al. (2010) who reduced the N fertilizer application rate in the early growth stages of directly seeded rice in southern Jiangsu Province by 65 kg N ha^{-1} and decreased the total N application rate by 50 kg N ha^{-1} compared to the local practice. The N uptake during the seedling stage of summer rice in the Tai Lake region was observed by Qiao et al. (2013) who found no differences in plant N between five different fertilizer N application rates, indicating that even the lowest N application rate could maintain normal rice growth during the early growth stage (Li et al. 2010; Qiao et al. 2013; Zhang et al. 2013).

For the winter wheat crop, most of the reductions in N fertilizer application rates should also be conducted at basal fertilization and for the first top-dressing in January during tillering stage. Due to the wet soil conditions, the high groundwater table and the drainage of the fields during the wheat season, the potential for N losses by denitrification and leaching is high (Cai et al. 2002; Ju et al. 2009; Zhang et al. 2013). It also needs to be taken into account that N uptake during the winter season is very low until February and the N mineralization capacity of the soils, in particular during the spring vegetation period of winter wheat is high enough to provide the plants with sufficient N during early growth stages. A nitrogen mineralization of 84 kg N ha^{-1} (0-100 cm soil profile) during the whole winter wheat growing period in the Taihu Region was simulated by Roelcke et al. (2002) based on an aerobic long-term incubation experiment without straw addition. In contrast to the North China Plain (NCP) and northern Jiangsu Province, winter temperatures in Yixing are relatively mild with a mean temperature in December, January and February of 5.4, 1.6 and 5.0 °C, respectively; therefore mineralization of organic N and crop residues is likely to continue over winter. Furthermore, it has been shown in our study that the residual mineral N content in the soil profile after the summer rice crop, consisting mainly of NH_4^+-N, can be as high as 50 kg N ha^{-1}. This mineral N can be regarded as fully available for the subsequent winter wheat crop and should be included in the derivation of N fertilization recommendations. In field experiments conducted by Cao et al. (2014) near Suzhou City, grain yield was not affected and N leaching was significantly decreased when the basal fertilizer N application rate was reduced by 45 kg N ha^{-1} with a total reduction of 75 kg N ha^{-1}. Similar findings were made in the NCP, where basal fertilizer N application to winter wheat could even be completely omitted if the N_{min} content in 0-0.3 m from sowing to tillering stage was higher than 30 kg N ha^{-1} (Zhao et al. 2006). However, in contrast to the NCP where fertilizer recommendations should be based on the demand of the whole winter wheat-summer maize double-cropping system (e.g., Hartmann et al. 2014), N transformation losses in the alternating moisture regime of the rice-wheat systems in southeastern China are high and only a small portion of residual N_{min} is available for the subsequent crop. Fertilizer recommendations should therefore be devised separately for summer rice and winter wheat crops.

2.5. Conclusions

The results of the three-year on-farm field experiments showed that a distinct reduction of current fertilizer N application rates to the rice-wheat double-crop rotation in the Taihu Region is possible without decrease in mean grain yields. Recommended N application rates in Yixing range between 200 and 230 kg N ha^{-1} (15-25 % reduction compared to farmers' practice) for summer rice, and around 170 to 180 kg N ha^{-1} (20-25 % reduction) to winter wheat. The greater reduction potential for mineral N fertilizers for winter wheat than for summer rice was also underlined by the agro-economic investigations. Fertilizer costs made up almost 50 % of total production costs in wheat production, though rice production was 50 % more profitable than wheat. Compared to the farmers´ conventional fertilization practice, reduced application rates of fertilizer N increased N efficiency indices only slightly, but led to significantly lower N balance surpluses after crop harvest. This was a clear indication for a reduction of N losses under the reduced fertilization regime. Another result of the decreased N surpluses was a significant reduction of residual mineral N after wheat harvest. Lower residual N contents in the soil profile in early June as well as during the winter wheat season indicate a reduced potential for N losses as a consequence of the flooding of the fields for the subsequent summer rice crop. Lower N contents in floodwater during the rice growing season lessen the risk of gaseous or leaching losses of N. Residual mineral N after summer rice was generally lower than after winter wheat. This study also shows the necessity of carrying out on-farm research over several seasons, with N application rates and single doses matching those of current farmers' practice, and taking into account varying weather conditions.

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3. Strategies for improving nitrogen use efficiency in a rice-wheat system in eastern China – Field experiments in Huai'an County

Abstract

Nitrogen (N) fertilization far beyond the crop demand and open field burning of crop residues (mainly rice and wheat straw) are a common practice in the intensive rice-wheat double-cropping system in northern Jiangsu Province in eastern China. While high N balance surpluses and low N use efficiencies (NUE) lead to immense losses of reactive N to water bodies (mainly NO_3^- and NH_4^+) and to the atmosphere (N_2 and N_2O), substantial amounts of CO_2, CH_4 and NO_x are being released through open field burning of straw. Field experiments on five replicate farmers' field sites were conducted in northern Jiangsu Province over three consecutive summer rice–winter wheat double-crop rotations with three different N fertilization treatments ('conventional' (farmers' practice), 'reduced' (by 31 % for wheat and 25 % for rice) and zero N application) and an agronomical 'x'-treatment within each fertilization level (incorporation of rice and wheat straw instead of removing the straw after harvest). The results of the field experiment demonstrated a significant reduction potential for N fertilizer application rates for both crops without decrease in grain yield. Mean grain yields of the whole double crop rotation were 13.1 Mg N ha^{-1} yr^{-1} under conventional fertilization practice and 13.0 Mg N ha^{-1} yr^{-1} under the reduced fertilization regime. Around 60 % of the overall N reduction was achieved by reducing the basal N fertilization in winter wheat and the tillering fertilization of summer rice. Potential N losses to the environment were considerably reduced, as the N balance surpluses of one crop rotation were significantly decreased from 320 kg N ha^{-1} yr^{-1} under conventional fertilization practice to 179 kg N ha^{-1} yr^{-1} under reduced N fertilization. Consequently, a significant increase in the NUE could be achieved in most years and crops under reduced fertilization compared to the farmers' practice. Incorporation of crop residues was easily managed with proper machinery and without affecting crop grain yields and can thus be recommended at least for summer rice straw to the winter wheat crop. Recommendations on the reduction of fertilizer N application rates were derived on the basis of experiments on farmers´ field sites and a reduction by 25-30 % for winter wheat and by 20-25 % for summer rice, compared to the present levels, is recommended.

3.1. Introduction

Agriculture in China has changed dramatically within the past 30 years from low-level farming systems with narrow nutrient cycles to very intensive farming systems with local and regional specialization and spatial separation of crop and livestock production. This development was favoured by a combination of a policy with prioritisation of food security and economic growth. In this context, newly-bred high-yielding rice varieties were introduced in the 1960s (Dalrymple 1986), and wide-spread use of mineral nitrogen (N) fertilizers in the 1970s. Changes occurred from relatively complex cropping systems with crop rotations including various crops to mostly single- and double-cropping systems.

One of the most important current double-cropping systems is irrigated summer rice (*Oryza sativa* L.) in rotation with winter wheat (*Triticum aestivum* L.). The highest area percentage of this system is in Jiangsu Province (Dawe et al. 2004) where the most ancient and intensive agricultural region is the Taihu Region in the south of Jiangsu Province and northern part of Zhejiang Province. However, at the same time, southern Jiangsu and the Taihu Region in particular, is one of the most economically developed areas of China (Schuurman and He 2013) and one of the regions with the highest urbanization level and speed of the country (Deng et al. 2015). As a consequence, major land use changes have been occurring, with high losses of arable land area resulting in a rapid decrease in highly fertile and productive soils (Lichtenberg and Ding 2008; Xu 2004). Therefore, to maintain food security for a large and still growing population, northern Jiangsu Province has gained importance for food production in the recent years. Similar to the Taihu Region, the predominant double-cropping system in northern Jiangsu is summer rice in rotation with an upland crop from November until May, mainly winter wheat or oilseed rape (*Brassica napus* L.). These double-crop rotations are characterized by high application rates of mineral N fertilizers and notably low N use efficiencies. The average fertilizer N application rate of a whole double crop rotation in northern Jiangsu ranges between 550 and 600 kg N ha^{-1} yr^{-1} and is even higher compared to the present N application rate in the rice-wheat double cropping system in southern Jiangsu.

The current excessive mineral N fertilizer application, lead to high N balance surpluses and consequently high losses of reactive N to the environment. The net anthropogenic N input of Jiangsu Province has been the highest of all Chinese provinces (except for Shanghai) for more than 30 years (Han et al. 2014). Environmental impacts of these N losses appear in elevated nutrient concentrations in groundwater and surface waters, causing a poor drinking water quality (Qin et al. 2010) and the widespread eutrophication of fresh water bodies (Conley et al. 2009; Cui et al. 2014a; Paerl et al. 2011). Furthermore, a decrease in soil pH was reported by Guo et al. (2010) in the main crop production regions of China, mainly due to the excessive use of mineral N fertilizers. Main N loss pathways differ among the crops of the double-cropping system. While most N losses during the summer rice season occur due to ammonia (NH_3) volatilization and denitrification (Cai et al. 2002; Freney et al. 1990), the main loss pathways during the winter wheat season arise from denitrification, nitrate (NO_3^-) leaching and runoff (Zhao et al. 2009; Zhao et al. 2012a). Ammonia losses measured *in situ* during the rice season under conventional fertilization practice of 300 kg N ha^{-1} in the Taihu Region ranged between 32 kg N ha^{-1} (Li et al. 2008) and 76 kg N ha^{-1} (Zhao et al. 2012b), while the apparent denitrification losses (calculated by difference method) in the same region ranged between 22 % (Zhao et al. 2012b) and 36 % (Ju et al. 2009) of N the applied to the rice crop. Even higher apparent denitrification losses were calculated by Ju et al. (2009) for the winter wheat crop in the

Taihu Region. They reported N losses as high as 44 % of total applied N, due to wet soil conditions, high temperatures and relatively high soil organic carbon (SOC) contents. Fertilizer N recovery efficiency in the rice-wheat system at the present N fertilization levels has been reported to commonly range between 20 and 35 %, with slightly higher efficiency of the winter wheat crop (Jin 2012; Ju et al. 2009).

Besides an improper N fertilization management, the treatment of crop residues after harvest in the rice-wheat double crop rotation has a massive impact on the environment and the air quality in particular. The common practice of open-field burning of crop residues leads to immense losses of soil organic carbon and soil nutrients, has adverse effects on the environment and human health, affects air and road transport, and releases substantial amounts of CO_2, CH_4 and NO_x to the atmosphere (Miura and Kanno 1997; Smil 1999). Despite the increased importance of northern Jiangsu Province for food production for the whole country there is a strong lack of field studies in this region, and it is therefore particularly important to evaluate the fertilizer management practice and N loss pathways. In contrast to the Taihu Region, which belongs to the northern subtropics, the pedologic and climatic conditions in northern Jiangsu are more comparable to the conditions in the North China Plain (NCP). Due to the differences between the natural conditions in southern and northern Jiangsu Province, results from field studies in the Taihu Region cannot readily be transposed to the northern part of the Province.

Two similar on-farm field studies for demonstration purposes were carried out in northern and in southern Jiangsu Province from 2008 to 2011. Results of the study in southern Jiangsu (Taihu Region) have been reported by Hofmeier et al. (2015), while this study presents results from northern Jiangsu Province. The objectives of the present study are to (1) quantify N loss potential for the rice-wheat system by balance calculations on a field scale, (2) identify measures to increase N use efficiency, (3) monitor mineral N contents under different N fertilization treatments, (4) give recommendations for optimized N fertilization practices for a summer rice-winter wheat double-crop rotation in northern Jiangsu Province and to (5) give recommendations for straw management for the rice-wheat system.

3.2. Material and Methods

3.2.1. Site characterization

Field experiments were conducted in a summer rice-winter wheat double cropping system in Lingqiao Township (33°35'N, 118°53'E), Huai'an county, northern Jiangsu Province, China from November 2008 to June 2011. The study area was located in an alluvial floodplain which had been exposed to natural flooding until the late 1950s when flood control measures made a continuous cultivation of irrigated summer rice and upland winter wheat or oilseed rape in a double-crop rotation possible. The region has a warm temperate climate with summer monsoon rainfall. The long-term mean temperature during the rice season from early July to late October is 23°C, the average precipitation in this period sums up to 563 mm. Mean temperature during the upland cropping season from early November to early June is 8.5°C and the average rainfall amounts to 297 mm. Meteorological data (rainfall and temperature) during the experimental period and at the long-term average are given in Figure 3.1. In the course of the investigation period, particular weather conditions occurred during the last winter wheat season with exceptionally cold temperatures and almost no precipitation from November 2010 to March 2011. Weather conditions were also exceptional during the first half of the last summer rice season with very heavy rainfall events shortly after transplanting in mid July 2011 and very high precipitation in August.

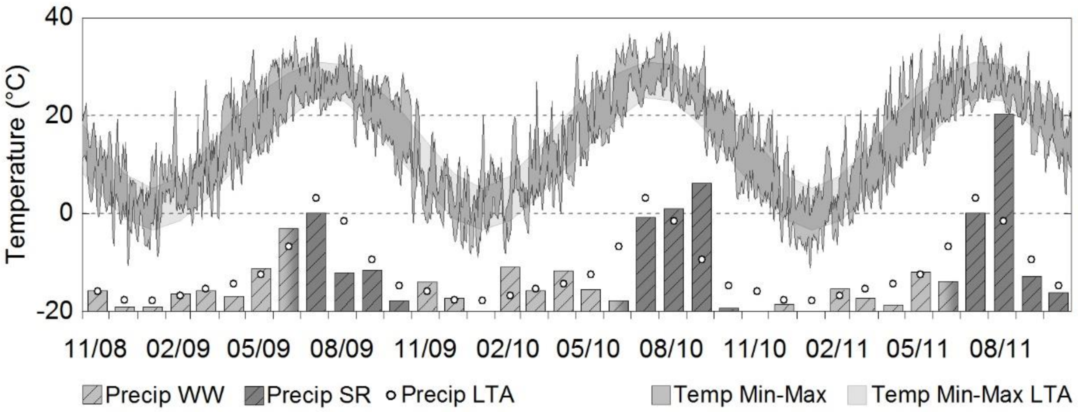

Figure 3.1: Precipitation (daily precipitation, cumulative monthly rainfall and long term average) and temperature (daily min. and max. during field experiment and long term average of min. and max.) during the three rice-wheat rotations (WW08/09 - SR11) in Huai'an.

The soil in Huai'an developed from lacustrine sediments and was classified as an Anthraquic Cambisol (IUSS Working Group WRB 2007) with a silty clay texture in the topsoil (0-0.2 m) and silty clay loam in the subsoil (Table 3.1). The soil was moderately alkaline with a pH of 8.3 in the topsoil and the presence of $CaCO_3$ throughout the 0-0.9 m profile. Soil samples were collected from 0-0.2, 0.2-0.6 and 0.6-0.9 m depth increments of a soil profile in March 2010. Soil samples were air-dried at room temperature, sieved to 2 mm, ground, homogenized and analysed for basic soil characteristics as listed in Table 3.1.

Table 3.1: Major soil characteristics of the experimental fields in Huai'an.

Depth	**pH** (H_2O)	**$CaCO_3$**	**SOC**	**N_{tot}**	**$K_{avail.}$**	**$P_{avail.}$**	**CEC**	**Bulk density**	**Sand**[a]	**Silt**	**Clay**
(m)		(%)	(%)	(%)	(mg kg^{-1})	(mg kg^{-1})	(cmol kg^{-1})	(g cm3)	(%)	(%)	(%)
0-0.2	8.3	8.9	1.8	0.22	215	13.2	22.2	1.29	1.8	53.5	44.8
0.2-0.6	8.4	9.0	1.0	0.08	160	2.1	18.2	1.5	11.5	57.7	30.8
0.6-0.9	8.4	8.2	0.7	0.08	158	3.5	17.5	1.23	0.9	70.4	28.8

[a] Sand: 2-0.063 mm; Silt: 0.063-0.002 mm; Clay: < 0.002 mm

3.2.2. Experimental set-up

The investigations included three consecutive double-crop rotations, starting with the sowing of the winter wheat (WW) crop in November 2008 and ending after the harvest of the third summer rice crop (SR) in early June 2011. The experiment was carried out in a split plot scheme, with five repetitions and followed the so called '3+x' approach. It contained three different N fertilization treatments (incl. zero N) as main factors, and an additional agronomical 'x'-treatment within each of the two fertilization levels as a sub-plot. The 'x'-treatment was established after the first summer rice crop (SR09) and was investigated for two consecutive double-crop rotations (WW09/10 - SR11). Nitrogen fertilization treatments were 'conventional' N fertilization (CN) according to the local farmers' practices and 'reduced' N fertilization (RN). An annually rotating zero-N microplot (zero N), 40 m^2 in size, was embedded in the CN subplots. Reductions of fertilizer N were 31 % and 25 % for wheat and rice, respectively. N fertilization rates for winter wheat crops are shown in Table 3.2 and for summer rice crops in

Table 3.3. The agronomical 'x'-treatment was adapted to the respective farmers' practices and consisted of incorporation of chopped rice and wheat straw instead of removing the straw on the field after harvest.

3.2.3. Crop management

Field preparation for winter wheat crop started directly after rice harvest with the removal of the rice straw in late October/early November. A uniform application of NPK compound fertilizer and additional urea fertilizer (Table 3.2) were broadcasted by hand just before incorporation of rice stubbles with a rotary tiller. Instead of NPK fertilizer, all zero N plots received 56 kg P ha^{-1} as triple superphosphate and 56 kg K ha^{-1} as KCl. After field preparation wheat seeds (cv. *huai mai* 20#, 280 kg seeds ha^{-1}) were broadcasted by hand and slightly incorporated into the soil. Split applications of N fertilizer were given as follows: 60-65 % at pre-seeding, 19-20 % during tillering in late January/early February and 16-20 % at tillering in mid-March (Table 3.2). Winter wheat plots were harvested with a combine harvester in late May-early June.

After winter wheat harvest all plots were flooded with canal water before tillage in order to prepare the fields for the subsequent summer rice crop. Field preparation started 5-10 days after flooding with incorporation of winter wheat stubbles followed by puddling (tillage of flooded soil) the topsoil and levelling the field to make it suitable for crop establishment. A basal fertilizer application with NPK compound fertilizer was broadcasted by hand to CN and RN plots just before the last step of field preparation and zero N plots received 45 kg P ha^{-1} as triple superphosphate and 45 kg K ha^{-1} as KCl for basal fertilization. Subsequently, 21 days old rice seedlings (cv. *lian geng* 6#) were transplanted manually by throwing the hills (about 3 seedlings per hill) into the field. Split applications of N fertilizer were given as follows: 15-20 % as basal dressing, 37-40 % at early tillering, 15 % at mid-tillering only to CN and 33-40 % at panicle initiation in mid-August (

Table 3.3). Additionally, all plots received 22.5 kg K ha^{-1} as KCl at panicle initiation. The fields were drained for mid-season aeration before panicle initiation in August and roughly four weeks before harvest. Summer rice plots were harvested with a combine harvester in late October.

Table 3.2: Amounts, types and dates of fertilizer N application to winter wheat crops from 2008 to 2011 in Huai'an.

Crop	**Treatment**	**Basal fertilization**		**Winter fertilization**		**Tillering fertilization**		**Total N per crop**
		(kg NPK ha^{-1})	Date	(kg N ha^{-1})	Date	(kg N ha^{-1})	Date	(kg N ha^{-1})
WW08/09	CN	106 urea + 56 NPK	11/17/08	52 urea	02/13/09	52 urea	03/08/09	266
	RN	70 urea + 56 NPK	"	35 urea	"	28 urea	"	189
WW09/10	CN	100 urea + 56 NPK	10/29/09	52 urea	02/09/10	52 urea	03/20/10	260
	RN	54 urea + 56 NPK	"	35 urea	"	28 urea	"	173
WW10/11	CN	100 urea + 56 NPK	10/29/10	52 urea	01/14/11	52 urea	03/19/11	260
	RN	54 urea + 56 NPK	"	35 urea	"	35 urea	"	180

Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization; zero N - unfertilized control w/o N application; NPK – NPK compound fertilizer (15% N); U – urea (46% N).

Table 3.3: Amounts, types and dates of fertilizer N application to summer rice crops from 2009 to 2011 in Huai'an.

Crop	**Treatment**	**Basal fertilization**		**Early tillering**		**Maximum tillering**		**Panicle stage**		**Booting stage**		**Total N per crop**
		(kg N ha^{-1})	Date	(kg N ha^{-1})	Date	(kg N ha^{-1})	Date	(kg N ha^{-1})	Date	(kg N ha^{-1})	Date	(kg N ha^{-1})
SR09	CN[a]	45 NPK[b]	06/29	90 urea	07/07	45 urea	07/14	75 urea	08/13	45 urea	08/18	300
	RN	45 NPK	"	75 urea	"	0	"	75 urea	"	30 urea	"	225
SR10	CN	45 NPK	07/01	110 urea	07/11	45 urea	07/18	100 urea	08/18	-	-	300
	RN	45 NPK	"	90 urea	"	0	"	90 urea	"	-	-	225
SR11	CN	45 NPK	07/04	110 urea	07/22	45 urea	07/27	100 urea	08/20	-	-	300
	RN	45 NPK	"	90 urea	"	0	"	90 urea	"	-	-	225

Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization; zero N - unfertilized control w/o N application; NPK – NPK compound fertilizer (15% N); U – urea (46% N).

For the agronomical 'x'-treatments beginning with the second wheat season (WW09/10), rice straw chopped by combine harvester was incorporated with a rotary tiller at soil preparation for the wheat crop. Beginning with the rice season 2010, incorporation of chopped wheat straw was done directly after wheat harvest, approximately three weeks before flooding of the field for the summer rice crops. Mean straw amounts, C and N contents and C/N ratios of incorporated crop residues to the agronomical 'x'-treatments are shown in Table 3.4.

Table 3.4: Mean straw amounts, C and N contents and C/N ratios of rice straw incorporated before winter wheat crops and wheat straw incorporated before summer rice crops to agronomical 'x'-treatments.

Crop	**Treatment**	**Straw amount** ($Mg\ ha^{-1}$)	**C content** ($kg\ kg^{-1}$)	**N content** ($kg\ kg^{-1}$)	**C/N**
WW09/10	CN-x	5.32 ± 0.54	38.0 ± 3.0	1.10 ± 0.10	35 ± 5
	RN-x	5.09 ± 0.35	39.5 ± 2.8	0.98 ± 0.12	41 ± 7
WW10/11	CN-x	4.92 ± 0.49	37.0 ± 0.6	0.81 ± 0.08	46 ± 6
	RN-x	4.87 ± 0.30	37.3 ± 0.2	0.87 ± 0.07	43 ± 4
SR10	CN-x	7.17 ± 0.44	43.9 ± 0.3	0.55 ± 0.01	80 ± 2
	RN-x	6.57 ± 0.55	44.1 ± 0.3	0.44 ± 0.07	101 ± 15
SR11	CN-x	2.90 ± 0.36	41.8 ± 0.1	0.56 ± 0.07	75 ± 9
	RN-x	3.07 ± 0.36	41.5 ± 0.1	0.53 ± 0.06	79 ± 9

Abbreviations: CN-x - conventional N fertilization practice with straw incorporation; RN-x - reduced N fertilization with straw incorporation.

3.2.4. Plant and soil sampling, sample preparation and analyses

Crop grain yields were quantified by harvesting the experimental plots as a whole and taking grain subsamples directly after harvest in order to determine grain moisture content. Grain yields were then adjusted to 14 % moisture content. Whole-plant samples were taken at physiological maturity for analyses of straw yield, yield components and above-ground N uptake. Samples were separated into different plant compartments and pre-dried for 1 h at 105°C followed by drying for 48 h at 80°C. Dry weights of plant organs were determined and subsamples were ground and mixed for subsequent N analysis via elemental analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Hanau, Germany). Above-ground N uptake was calculated by multiplying N concentration in plant samples with above-ground dry matter amount.

Mineral N (N_{min} = NO_3^--N + NH_4^+-N) contents in the soil profiles were determined directly after harvest of summer rice and winter wheat crops as well as before each fertilizer application event during the winter wheat season. Four 0.9 m deep soil cores were randomly taken from each subplot, separated into 0-0.2, 0.2-0.6 and 0.6-0.9 m depth increments and stored at 4°C during transport and until further processing. The field-moist soil samples were homogenized and extracted mostly within one day with 1 M KCl by shaking for 1 h with a 1:4 (w/w) soil:solution ratio. Soil extracts were analyzed for NO_3^--N and NH_4^+-N using a continuous-flow autoanalyzer (SKALAR, San Plus System, Breda, The Netherlands). For the conversion of N_{min} contents to an area basis (kg N ha^{-1}), actual bulk densities determined separately were used.

3.2.5. Agronomic indicators

A set of indicators for N use efficiency and the effect of N fertilization on grain yields was chosen. Agronomic indices used for the estimation of N use efficiency included apparent recovery efficiency (RE_N) and agronomic efficiency (AE_N) of applied N. These efficiencies were calculated based on the difference between N uptake in above-ground biomass and crop yields between fertilized plots and an unfertilized control, as described by Craswell and Godwin (1984). The RE_N expresses the uptake efficiency of fertilizer N, while the AE_N describes the yield increase per unit fertilizer applied and is the overall efficiency with which N is used by the crop. Additionally, to indicate the effect of N fertilization on grain yields, the partial productivity of N fertilization (PFP_N) and the yield response (Y_Δ) to N fertilizer application (N response) were used. The indicators were calculated as follows:

$$RE_N = (U_N - U_0) / F_N \qquad (\text{kg kg}^{-1})$$

$$AE_N = (Y_N - Y_0) / F_N \qquad (\text{kg kg}^{-1})$$

$$PFP_N = Y_N / F_N \qquad (\text{kg kg}^{-1})$$

$$Y_\Delta = Y_N - Y_0 \qquad (\text{Mg ha}^{-1})$$

in which Y_N and Y_0 are the grain yields (Mg ha^{-1}) with and without fertilizer N input, U_N and U_0 are the total N uptake (kg N ha^{-1}) in above-ground biomass at physiological maturity with and without N input, and F_N is the amount of applied N fertilizer (kg N ha^{-1}).

3.2.6. Nitrogen balance calculations

Simple soil surface balances at field scale level were calculated as the difference between N inputs (N from mineral fertilizer application, by atmospheric wet and dry deposition, irrigation water and asymbiotic biological N fixation (BNF)), and outputs (N removed with grain and straw) separately for both crops, for the whole double-crop rotation and for both fertilization treatments. The difference between inputs and outputs reveals the N surplus or deficit. Nitrogen from atmospheric deposition, irrigation water and BNF were included in the calculation based on literature in order to make the balances comparable with those from other experiments. However, these values were obtained from studies in the NCP and the Taihu Region, as there are no such published measurements from northern Jiangsu. The agri-environmental indicator (AEI) 'N surplus' (expressed in kg N ha^{-1} yr^{-1} or per $crop^{-1}$) is an indicator for the N loss potential via different pathways.

3.2.7. Statistical analyses

Statistical analyzes were performed using OriginPro Software. The differences in grain yields, above-ground N uptake, agronomic and agri-environmental indicators as well as N_{min} contents between the treatments were tested for statistical significance. Student´s t-test was applied when the variance of the means between both N fertilized treatments was calculated. When comparing means of all three treatments, an ANOVA was performed. Differences were tested for significance using Tukey's range test.

3.3. Results

3.3.1. Grain yield and N uptake

No significant differences in winter wheat grain yields were observed between CN and RN in any of the three years (Figure 3.2). Grain yields were 0.32 Mg ha^{-1} higher under RN compared to CN in the first, 0.01 Mg ha^{-1} lower under RN in the second, and 0.50 Mg ha^{-1} higher under RN in the third year. Mean grain yield under RN for all three winter wheat crops was 0.27 Mg ha^{-1} higher compared to CN (not significant, *n.s.*). Incorporation of plant residues from the previous rice crop had no consistent effects on grain yields under both N fertilization treatments. However, significantly higher yields could only be observed in WW09/10 under CN-x compared to CN and RN-x ($P < 0.05$). The average grain yield under zero N across the years was 3.43 Mg ha^{-1}, with highest yields in WW09/10 and lowest yields in WW10/11. Because of the unfavourable weather conditions during the last winter wheat season (see 3.2.1), yields of all treatments in WW10/11 were about 1.7 Mg ha^{-1} lower than in the previous years.

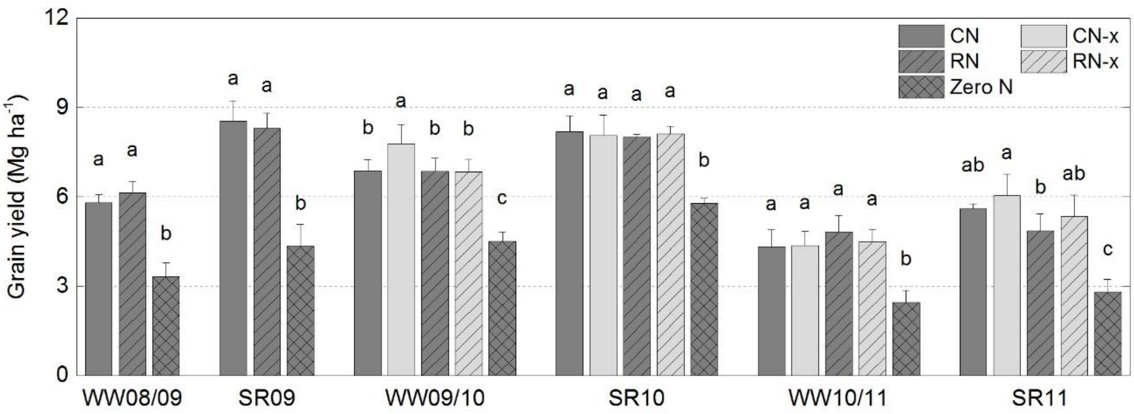

Figure 3.2: Grain yield of winter wheat and summer rice crops at Huai'an, China (bars: mean values; error bars: ± s.d., n=5)

Similar to the grain yield, the above-ground N uptake of winter wheat did not differ between CN and RN (Figure 3.3). Average N uptake was 145 kg N ha^{-1} for both CN and RN, with a slightly higher N uptake of RN in the first year (by 10.3 kg N ha^{-1}) and in the third year (by 3.8 kg N ha^{-1}) and a higher N uptake for CN in the second year (by 14.2 kg N ha^{-1}). In the 'x'-treatments, similarly to the effect observed on grain yield, N uptake increased significantly ($P < 0.05$) in WW09/10 under CN-x compared to CN and RN-x, but a consistent effect of straw incorporation on N uptake could not be observed under both N fertilization treatments. Average N uptake under zero N was 70.2 kg N ha^{-1}, with similar plant N uptake in the first two years and a very low N uptake in the third year.

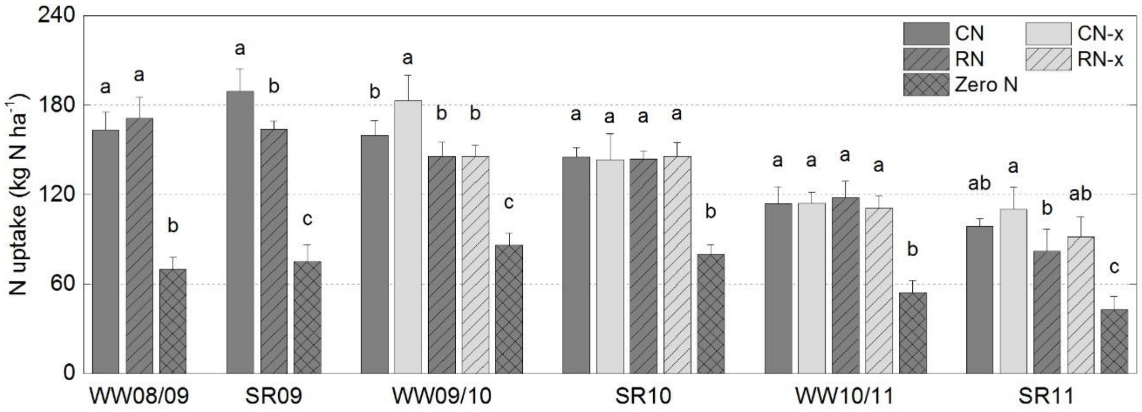

Figure 3.3: Above-ground N uptake of winter wheat and summer rice crops at Huai'an, China (bars: mean values; error bars: ± s.d., n=5).

For summer rice, mean grain yields for all three crops across the three years were 0.39 Mg ha^{-1} lower under RN compared to CN (*n.s.*). A slight yield decline under RN occurred in all three years with 2.8 % (0.24 Mg ha^{-1}) in the first year (*n.s.*), 2.2 % (0.18 Mg ha^{-1}) in the second year (*n.s.*) and a significant (P < 0.01) decline by 13.1 % (0.74 Mg ha^{-1}) in the third year (Figure 3.2). Straw incorporation from the previous wheat crop had no influence on grain yield for all three summer rice crops under both N fertilization levels. For the zero N plots, the grain yield ranged from 2.81 Mg ha^{-1} in SR11 to 5.97 Mg ha^{-1} in SR10 and was 4.37 Mg ha^{-1} as mean over all three cropping seasons. The comparatively high yields of SR10 were partly due to water intrusion into two of the five zero N plots from adjacent CN plots. The average grain yield of the summer rice plots in the third year was 2.8 Mg ha^{-1} lower compared to the previous years due to heavy rain events in July (see 3.2.1, Figure 3.1) with the consequence of a severely delayed tillering fertilization.

Above-ground plant N uptake by summer rice on average decreased by 15.7 kg N ha^{-1} under RN compared to CN, with a lower N uptake in the reduced fertilized treatments occurring in all three years (Figure 3.3). However, the decrease was significant (P < 0.01) only in the first rice cropping season (27.3 kg N ha^{-1}), but not in the second (1.9 kg N ha^{-1}) nor in the last season (18.2 kg N ha^{-1}). Average N uptake under zero N was 67.7 kg N ha^{-1}. Slight differences (*n.s.*) in above-ground N uptake in the 'x'-treatments only occurred in SR11, with higher uptake in treatments with straw incorporation.

3.3.2. Agronomic indicators

All indicators for N use efficiency of winter wheat increased significantly (P < 0.05) under RN compared to CN by 11.3 kg kg^{-1}, 5.3 kg kg^{-1} and 0.12 kg kg^{-1} for PFP_N, AE_N and RE_N, respectively (Table 3.5). The PFP_N and AE_N was significantly higher under RN in all three growing seasons (P < 0.01 in WW08/09 and WW09/10, P < 0.05 in WW10/11), while for RE_N a significant increase under RN was observed in WW08/09 (P < 0.01) and in WW10/11 (P < 0.05). Average yield response of winter wheat crops to fertilizer N application was 12 % higher in RN (Y_Δ = 2.50 Mg ha^{-1}) compared to CN (Y_Δ = 2.23 Mg ha^{-1}), with an average grain yield for zero N of 3.43 Mg ha^{-1}.

Table 3.5: N response and N use efficiency indicators for the winter wheat seasons from 2008/09 to 2010/11 in Huai'an.

Crop	**Treatment**	**N response** (Mg ha^{-1})	**PFP$_N$** (kg kg^{-1})	**AE$_N$** (kg kg^{-1})	**RE$_N$** (kg kg^{-1})
WW08/09	CN	2.49 ± 0.27 a	21.8 ± 1.0 a	9.4 ± 1.0 a	0.35 ± 0.04 a
	RN	2.81 ± 0.39 a	32.4 ± 2.1 b	14.8 ± 2.1 b	0.54 ± 0.07 b
WW09/10	CN	2.36 ± 0.36 a	26.4 ± 1.4 a	9.1 ± 1.4 a	0.28 ± 0.03 a
	RN	2.35 ± 0.44 a	39.7 ± 2.5 b	13.6 ± 2.5 b	0.34 ± 0.05 a
WW10/11	CN	1.85 ± 0.59 a	16.6 ± 2.3 a	7.1 ± 2.3 a	0.23 ± 0.04 a
	RN	2.35 ± 0.56 a	26.8 ± 3.1 b	13.1 ± 3.1 b	0.35 ± 0.06 b
Mean	CN	2.23 ± 0.49 a	21.6 ± 4.4 a	8.5 ± 1.8 a	0.29 ± 0.06 a
	RN	2.50 ± 0.49 a	32.9 ± 6.0 b	13.8 ± 2.5 b	0.41 ± 0.11 b

Means followed by different letters were significantly different at α = 0.05 according to Student´s t-test.
Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization; PFP$_N$: partial factor productivity; AE$_N$: agronomic efficiency; RE$_N$: apparent recovery efficiency.

For summer rice, a significant ($P < 0.05$) increase in the agronomic indicators was only observed for the PFP$_N$ that was 6.6 kg kg^{-1} higher under RN compared to CN. An increase in AE$_N$ under RN compared to CN could be observed in the first two growing seasons but this was significant ($P < 0.05$) only in SR09 (Table 2.6). Mean AE$_N$ over all three growing seasons increased slightly under RN by 1.8 kg kg^{-1} (*n.s.*). Similar to the AE$_N$, the RE$_N$ was higher under RN compared to CN in SR09 and SR10, with a significant ($P < 0.05$) increase by 0.06 kg kg^{-1} only in SR10. In average of all three rice growing seasons, the RE$_N$ under RN and CN were at a similar level with a slightly higher RE$_N$ under RN (*n.s.*). Average yield response of summer rice crops to fertilizer N application was 12 % lower for RN (Y_Δ = 2.75 Mg ha^{-1}) compared to CN (Y_Δ = 3.13 Mg ha^{-1}), with an average grain yield of 4.2 Mg ha^{-1} in the zero N plots (Table 2.6).

Table 3.6: N response and N use efficiency indicators for the summer rice seasons from 2009 to 2011 in Huai'an.

Crop	**Treatment**	**N response** (Mg ha^{-1})	**PFP$_N$** (kg kg^{-1})	**AE$_N$** (kg kg^{-1})	**RE$_N$** (kg kg^{-1})
SR09	CN	4.20 ± 0.69 a	28.5 ± 2.3 a	14.0 ± 2.3 a	0.38 ± 0.05 a
	RN	3.96 ± 0.53 a	36.9 ± 2.4 b	17.6 ± 2.4 b	0.39 ± 0.02 a
SR10	CN	2.40 ± 0.53 a	27.3 ± 1.8 a	8.0 ± 1.8 a	0.22 ± 0.02 a
	RN	2.22 ± 0.10 a	35.6 ± 0.5 b	9.9 ± 0.5 a	0.28 ± 0.03 b
SR11	CN	2.80 ± 0.16 a	18.7 ± 0.5 a	9.3 ± 0.5 a	0.19 ± 0.02 a
	RN	2.06 ± 0.56 b	21.6 ± 2.5 b	9.2 ± 2.5 a	0.17 ± 0.07 a
Mean	CN	3.13 ± 0.93 a	24.8 ± 4.8 a	10.4 ± 3.1 a	0.26 ± 0.09 a
	RN	2.75 ± 0.98 a	31.4 ± 7.4 b	12.2 ± 4.4 a	0.28 ± 0.10 a

Means followed by different letters were significantly different at α = 0.05 according to Student´s t-test.
Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization; PFP$_N$: partial factor productivity; AE$_N$: agronomic efficiency; RE$_N$: apparent recovery efficiency.

3.3.3. Nitrogen balance calculations

The calculated nitrogen input/output balances on field scale basis showed distinct differences between both crops and treatments. Compared to summer rice, total N input to winter wheat was 13 % lower under CN and 20 % lower under RN, while the N output was almost equal between both crops under CN and slightly higher in winter wheat than in summer rice under RN (Table 3.7). As a consequence, the calculated N balance surplus of winter wheat was 25 % (46 kg N ha^{-1} $crop^{-1}$) and 53 % (65 kg N ha^{-1} $crop^{-1}$) lower compared to summer rice under CN and RN, respectively. Nitrogen input to CN and RN differed only regarding the total amount of applied mineral N fertilizer. This was reduced under RN by 31 % for winter wheat and by 25 % for summer rice. The resulting N balance surplus of winter wheat was 58 % (80 kg N ha^{-1} $crop^{1}$) and that of summer rice was 33 % (61 kg N ha^{-1} $crop^{-1}$) lower in RN compared with CN.

Table 3.7: Mean soil surface N balances (n=15) of three consecutive years (2008/09-2011) per ha for rice and wheat crops and for the complete double-crop rotation of conventional (CN) and reduced (RN) fertilized treatments in Huai'an.

N in-/output balance	**Summer rice**		**Winter wheat**		**Rice-wheat rotation**	
	CN	RN	CN	RN	CN	RN
Grain yields (Mg ha^{-1})	7.44 ± 1.43	7.06 ± 1.66	5.67 ± 1.16	5.94 ± 0.98	13.11 ± 2.45	12.99 ± 2.50
Input (kg N ha^{-1})	**327 ± 0 *****	**252 ± 0 *****	**283 ± 3 *****	**202 ± 7 *****	**610 ± 3 *****	**454 ± 7 *****
Mineral N fertilizer	300 ± 0	225 ± 0	262 ± 3	181 ± 7	562 ± 3	406 ± 7
Other N inputs‡	27	27	21	21	48	48
Output (kg N ha^{-1})	**144 ± 39**	**130 ± 37**	**146 ± 26**	**145 ± 25**	**290 ± 62**	**275 ± 60**
N in grain	101 ± 27	93 ± 26	121 ± 20	122 ± 22	222 ± 46	215 ± 44
N in straw	43 ± 13	37 ± 13	25 ± 9	23 ± 6	68 ± 17	60 ± 17
Surplus (kg N ha^{-1})	**183 ± 39 *****	**122 ± 37 *****	**137 ± 24 *****	**57 ± 23 *****	**320 ± 60 *****	**179 ± 58 *****

‡ Atmospheric N deposition (9 kg N ha^{-1} during rice season, 16 kg N ha^{-1} during wheat season; Zhai et al. 2009), irrigation water (10 kg N ha^{-1} during rice season; Zhao et al. 2012c) and BNF (8 kg N ha^{-1} during rice season (Roger and Ladha 1992a), 5 kg N ha^{-1} during wheat season (Ledgard and Giller 1995)).

*** significant difference between treatments within crops and double-crop rotation at 0.001 probability levels.

The by far major N input to the rice-wheat double crop rotation is through mineral N fertilizer, which accounts for 92 % and 89 % of total N input to CN and RN, respectively (Table 3.7). Other N inputs are through atmospheric N deposition (4-6 %), biological N fixation (2-3 %) and the N input with irrigation water during the rice season (2 %) (Figure 3.4). The annual N input under RN was decreased by 26 %, the total N output decreased by 5 % and in consequence, the calculated N balance surplus decreased by 44 % (141 kg N ha^{-1} yr^{-1}) compared to the CN treatment.

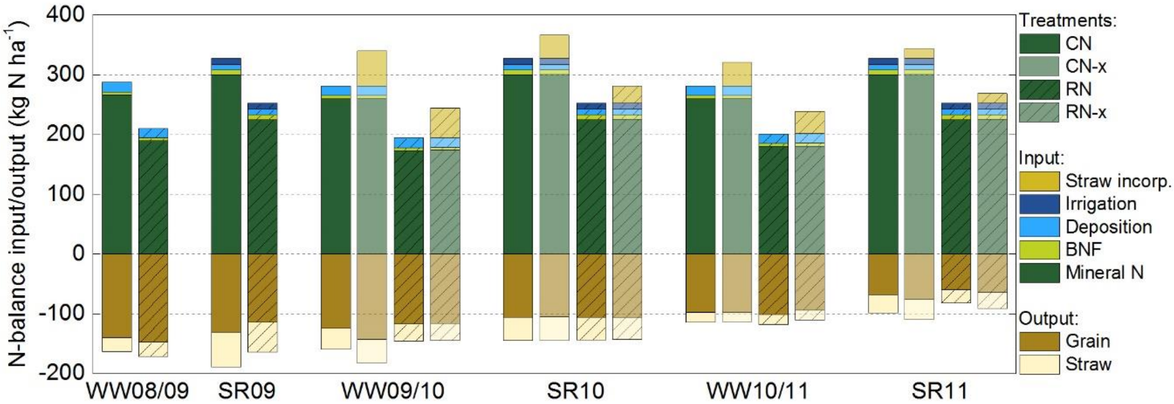

Figure 3.4: Input and output elements in kg N ha^{-1} for N balance calculations on plot scale for winter wheat and summer rice crops of conventional and reduced fertilized treatments without (CN, RN) and with (CN-x, RN-x) straw incorporation from WW08/09 to SR11 at Huai'an, China (piled bars: mean values; n=5).

Nitrogen inputs to the 'x'-treatments were considerably higher due to the retention and incorporation of crop residues from the previous crop (Figure 3.5). Additional N inputs to winter wheat were almost twice as high as those to summer rice (Table 3.8), due to the higher N content of rice straw compared to wheat straw (see section 3.2.3). Assumed that the N in crop residues was not prone to losses and that it was mineralized during the following cropping seasons, the calculated average N balance surplus of the whole double crop rotation in the 'x'-treatments was 90 kg N ha^{-1} yr^{-1} higher compared to the treatments with straw removal.

Table 3.8: Mean soil surface N balances (n=10) of two consecutive years (2009/10-2011) per ha for rice and wheat crops and for the complete double-crop rotation of conventional (CN-x) and reduced (RN-x) fertilized agronomical 'x'-treatments in Huai'an.

N in-/output balance	**Summer rice**		**Winter wheat**		**Rice-wheat rotation**	
	CN	RN	CN	RN	CN	RN
Grain yields (Mg ha^{-1})	7.05 ± 1.25	6.73 ± 1.55	6.07 ± 1.88	5.66 ± 1.30	13.1 ± 2.97	12.4 ± 2.80
Input (kg N ha^{-1})	**355 ± 12** ***	**275 ± 7** ***	**330 ± 9** ***	**243 ± 5** ***	**685 ± 24** ***	**516 ± 11** ***
Mineral N fertilizer	300 ± 0	225 ± 0	260 ± 0	177 ± 4	560 ± 0	402 ± 4
Straw from previous crop	28	±	12	23	±	7
Other N inputs‡	27	27	21	21	48	48
Output (kg N ha^{-1})	**127 ± 23**	**119 ± 30**	**149 ± 38**	**128 ± 20**	**276 ± 56**	**247 ± 49**
N in grain	90 ± 18	86 ± 24	121 ± 26	106 ± 13	211 ± 41	192 ± 36
N in straw	37 ± 7	32 ± 7	28 ± 12	23 ± 7	64 ± 16	55 ± 14
Surplus (kg N ha^{-1})	**228 ± 17** ***	**156 ± 24** ***	**181 ± 29** ***	**113 ± 17** ***	**409 ± 33** ***	**269 ± 40** ***

‡ Atmospheric N deposition (9 kg N ha^{-1} during rice season, 16 kg N ha^{-1} during wheat season; Zhai et al. 2009), irrigation water (10 kg N ha^{-1} during rice season; Zhao et al. 2012c) and BNF (8 kg N ha^{-1} during rice season (Roger and Ladha 1992a), 5 kg N ha^{-1} during wheat season (Ledgard and Giller 1995)).

*** significant difference between treatments within crops and double-crop rotation at 0.001 probability levels.

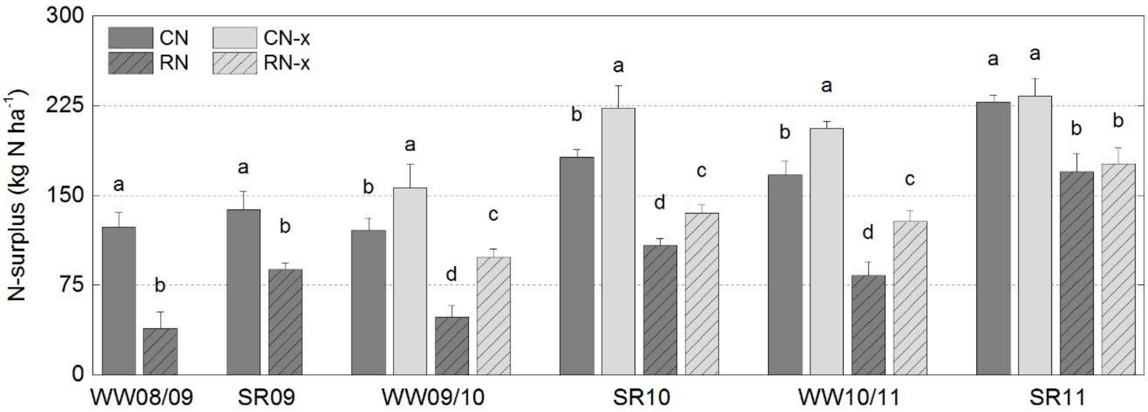

Figure 3.5: Mean soil surface N balance surpluses in kg N ha^{-1} for winter wheat and summer rice crops of conventional and reduced fertilized treatments without (CN, RN) and with (CN-x, RN-x) straw incorporation from WW08/09 to SR11 at Huai'an, China (bars: mean values; error bars: ± s.d., n=5).

3.3.4. Residual mineral N after crop harvest

Residual mineral N contents in the 0-0.9 m soil profile after winter wheat crops were generally higher under CN compared to RN and zero N treatments (Figure 3.6). However, significantly ($P < 0.05$) higher N_{min} contents under CN were only observed after WW08/09 growing season. Except for the first growing seasons, mineral N contents at wheat harvest under RN were at a similar level as N_{min} contents under zero N. Mineral N contents under CN ranged from 54.8 kg N ha^{-1} 0.9 m^{-1} after WW09/10 to 93.7 kg N ha^{-1} 0.9 m^{-1} after WW10/11 growing season. Under RN and zero N, the N_{min} contents ranged from 29.8 kg N ha^{-1} 0.9 m^{-1} after WW08/09 under zero N to 58.7 kg N ha^{-1} 0.9 m^{-1} after WW10/11 growing season under RN. There were no differences in NH_4^+-contents between the treatments. Mean NH_4^+-N contents were 7.2, 25.2 and 30.3 kg NH_4^+-N ha^{-1} 0.9 m^{-1} after WW08/09, WW09/10 and WW10/11, respectively. However, differences in NO_3^--N contents were clearly evident with significantly ($P < 0.05$) higher contents under CN compared to RN and zero N after WW08/09 and WW10/11. After summer rice harvest, there was no significant difference in residual N_{min} contents in the soil profile between the treatments in all years (Figure 3.6). Mean mineral N contents for all treatments were 51.5, 61.2 and 31.6 kg N ha^{-1} 0.9 m^{-1} after the SR09, SR10 and SR11 growing season, respectively.

The incorporation of crop residues had no significant effect on the N_{min} contents in the soil after winter wheat or summer rice seasons for both N fertilization treatments. However, N_{min} contents in the 'x'-treatments slightly decreased after WW09/10 and increased after WW10/11 as compared to the treatments without straw incorporation.

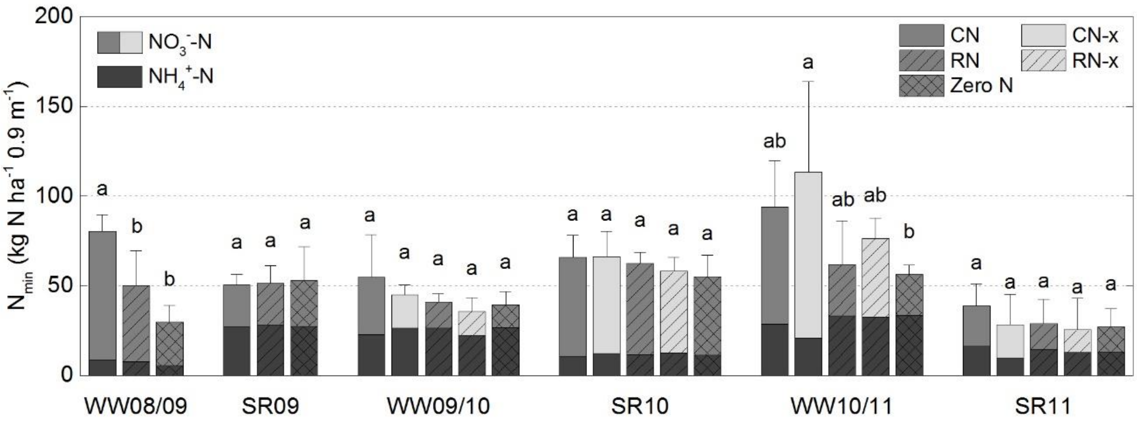

Figure 3.6: Mean residual N_{min} (NO_3^--N and NH_4^+-N) contents in 0-0.9 m depth after harvest of winter wheat and summer rice crops at Huai'an, China (bars: mean values; error bars: ± s.d., n=5).

3.4. Discussion

3.4.1. Grain yields and PFP_N

An average reduction of the mineral N fertilizer application rate by 28 % for the whole three-year summer rice-winter wheat double crop rotation decreased the total grain yield of the rotation by only 1 %. (*n.s.*) However, differences of the N reduction potential for mineral N fertilizers could be observed among the two crops. This potential can be considered to be high particularly for winter wheat, as the grain yield of wheat under RN where the N fertilization rate was reduced by 31 % was at the same level or even higher as the conventional N fertilization treatment. Conversely, the N reduction potential for summer rice can be assumed to be somewhat less than the applied reduction of 25 %, because grain yields under the reduced N fertilization treatments were considerably lower in all three years and this effect being significant in the third year.

In addition to yield differences due to N fertilization, considerably greater yield differences could be observed between the years. The yield level of the winter wheat crops under CN and RN was between 6.9 and 5.8 Mg ha^{-1} in WW08/09 and WW09/10, respectively, which was in the same range as other reported wheat grain yields in the rice-wheat cropping system in southern Jiangsu Province (Cao et al. 2014; Hofmeier et al. 2015; Ma et al. 2010; Ma et al. 2013; Wang et al. 2004) and in the maize-wheat rotation in the North China Plain (Hartmann et al. 2014; Ju et al. 2009; Liu et al. 2003; Xu et al. 2009; Zhao et al. 2006). Similar studies to ours have so far not been conducted in northern Jiangsu Province. The particularly low grain yields in WW10/11 were caused by a very poor field emergence due to the dry weather conditions after sowing, with only 15 mm of total precipitation from November to the beginning of February. This led to a poor crop stand and a very patchy crop in all treatments.

Grain yields of the first two summer rice crops under CN and RN were in the expected range of 8-9 Mg ha^{-1}, which is comparable with average grain yields of summer rice under farmers´ N fertilization practice for transplanted as well as direct seeded rice in Jiangsu Province (Hofmeier et al. 2015; Peng et al. 2006; Qiao et al. 2013). The considerably lower grain yields of SR11 were caused by a poor crop establishment after transplanting, caused by heavy rainfall and high water levels in the ponded rice fields, which led to a low tiller and thus panicle number. Moreover, the extremely high precipitation in August of more than 400 mm and a low radiation during the reproductive stage before flowering had negative effects on spikelet number, which is highly correlated with radiation and temperature (de Datta 1981).

A valuable indicator to describe the overall efficiency, in economic terms, is the PFP for applied N, as it provides an integrative index of the total economic output (grain yield) relative to the utilization of all N inputs to the system, including indigenous N of the soil(-floodwater) system and applied N fertilizers (Yadav 1998). In case of the rice-wheat cropping system of northern Jiangsu, the PFP_N of CN ranged between 20-25 kg kg^{-1}, without significant differences between the two crops. These PFP_N values are comparable with values calculated from official statistical data (17 and 29 kg kg^{-1} for wheat and rice, respectively) by Chai et al. (2013), who reported a strong decrease of PFP_N from the 1990s to the 2000s, but slightly lower compared to recently published values for the rice-wheat cropping system in the Taihu Region, that range between 30 and 35 kg kg^{-1} (Hofmeier et al. 2015). Lower PFP_N values in northern Jiangsu compared to the Taihu Region are an indicator for a poorer agricultural practice, i.e. higher fertilizer N inputs and improper crop management in combination with low grain yields. Possibilities to increase the PFP_N are by increasing the amount, uptake and utilization of indigenous N resources, and by increasing the efficiency with which applied N is taken up by the crop and utilized to produce grain (Cassman et al. 1998). In our study, PFP_N values could significantly be increased under the reduced N fertilization treatments of both crops, indicating an increased utilization of indigenous N sources. However, calculated PFP_N values were still considerably lower than the global average PFP_N for cereal production of about 44-52 kg kg^{-1} as reported by Ladha et al. (2005) and Dobermann (2007).

3.4.2. Nitrogen response and AE_N

Average grain yields (over three years) of zero N treatments were relatively low in both crops, which led to comparably high average yield responses to mineral N fertilization of 2.37 Mg ha^{-1} and 2.88 Mg ha^{-1} for winter wheat and summer rice, respectively. These yield responses are considerably higher than those commonly reported for China, with about 1.7 Mg ha^{-1} for wheat (Chuan et al. 2013) and 1.5 Mg ha^{-1} for rice (Peng et al. 2010). As the yield response is directly affected by the indigenous N supply from soil and environmental sources, it can be assumed that these N inputs are not as high in Huai'an as in other areas of China with intensive agriculture like the Taihu Region or the NCP.

Despite the comparatively high yield responses for wheat and rice, the calculated mean AE_N under CN was low for both crops. The AE_N for wheat in northern Jiangsu is comparable with the average AE_N for wheat in China (8.3 kg kg-1, Li et al. 2013) and the Taihu Region (8.8 kg kg-1; Hofmeier et al. 2015). The AE_N for rice was lower compared to the average AE_N for rice in China (12.6 kg kg-1; Li et al. 2013) and the Taihu Region (12.9 kg kg-1; Hofmeier et al. 2015). Even though we were able to increase the AE_N of wheat significantly by 63 % to 13.8 kg kg^{-1} and that of rice slightly by 17 % to 12.2 kg kg^{-1} under RN, these values are still lower than the world average AE_N for cereal crop production of 18 kg kg^{-1} calculated by Ladha et al. (2005). However, in a broad investigation of a site-specific nutrient management (SSNM) approach for intensive rice cropping systems in Asia by

Dobermann et al. (2002), the mean AE_N of rice under SSNM was only 14.8 kg kg^{-1}. As the AE_N is the ratio of yield response to the amount of applied mineral N fertilizer, it can either be increased by a grain yield increase or by a decrease of total N fertilization rate. Because the yield potential of the grown varieties was nearly reached under the current cropping practice, measures to improve the AE_N must either be in the breeding of new varieties with a higher yield potential or in the better fertilizer N management to reduce N losses.

3.4.3. Nitrogen uptake and RE_N

The average above-ground N uptake of winter wheat in Huai’an under CN and RN (145 kg N ha^{-1}) was slightly higher compared to the N uptake of wheat varieties grown in southern Jiangsu Province, which is between 100-130 kg N ha^{-1} with N application rates of 200-225 kg N ha^{-1} (Hofmeier et al. 2015; Jing et al. 2009; Zhao et al. 2012b), and considerably lower compared to the N uptake of winter wheat grown in the NCP, which was reported to be 160 kg N ha^{-1} (Cui et al. 2010b) and 178 kg N ha^{-1} (Cui et al. 2008b). However, the average N application rate of 325 kg N ha^{-1} (Cui et al. 2010b; Ju et al. 2009) to winter wheat grown in the wheat-maize rotation under farmers’ N practice in the NCP was much higher compared to wheat in the rice-wheat rotation. Due to the combination of high N application rates with an high indigenous N supply from soil (i.e. high soil N_{min} contents) and environmental sources (Cui et al. 2008a), the average RE_N for winter wheat in the NCP was only 0.18 kg kg^{-1} (Cui et al. 2008b) and significantly lower compared to the RE_N of winter wheat crops in the rice-wheat system ranging from 0.29 kg kg^{-1} in northern Jiangsu (this study) to 0.37 kg kg^{-1} (Hofmeier et al. 2015) and 0.49 kg kg^{-1} (Zhao et al. 2009) in the Taihu Region. As the soil N_{min} content at sowing of winter wheat is generally much lower in the rice-wheat system compared to the maize-wheat system and other environmental N sources like N deposition are lower as well, the indigenous N supply to wheat in rotation with rice is significantly lower.

The mean above-ground N uptake of around 137 kg N ha^{-1} by rice under CN and RN was relatively low in comparison with the mean N uptake of rice in farmers´ field sites in Jiangsu Province reported by Peng et al. (2006). They found an average N uptake of 233 kg kg^{-1}, which was generally higher compared to other rice growing regions of China. As a consequence of the relatively low N uptake in combination with high N application rates, the mean RE_N of summer rice (0.27 kg kg^{-1} for CN and RN) was lower than values published in the 1990s by Zhu (1997a) who estimated an RE_N for rice production in China of 0.38 kg kg^{-1} and recently by Hofmeier et al. (2015) who reported a RE_N of 0.40 kg kg^{-1} for irrigated rice in the Taihu Region. However, most of the reported RE_N values were determined in researcher-managed plots in farmers´ field sites, rather than estimations from on-farm assessments. These on-farm assessments tend to result in 25 % lower RE_N values (Ladha et al. 2005), because of differences in the scale of farming operations and in N-management practices. Nevertheless, compared to intensive rice systems in Asia under SSNM where the RE_N can exceed 0.5 kg kg^{-1} (Dobermann et al. 2002), most published values for RE_N for rice in China are considerably lower.

3.4.4. Nitrogen loss potential

The N loss potential of the rice-wheat double crop rotation can roughly be estimated from the calculated N surpluses of the two crops. Mean N balance surpluses derived after the removal of grain and straw were generally higher for summer rice than for winter wheat, both under CN and RN. Thus the N loss potential was higher during the summer rice crop. However, our results show that the potential for a reduction of the mineral N fertilizer application under the common farming practices is more pronounced for winter wheat. This implies that efficient measures to reduce the N surpluses in summer rice production are only possible with simultaneous implementation of better adapted farming practices regarding crop, soil, water and fertilizer management. Nevertheless, looking at the whole double-crop rotation, the reduction potential for the application of mineral N fertilizer shows that the overall potential N losses can be easily reduced by nearly half with simple measures and without major changes in the farming practices.

The main potential N loss pathways during the winter wheat crop are probably N leaching (mainly as NO_3^--N but also dissolved organic nitrogen, DON) and denitrification. Due to high groundwater tables and mostly wet soil conditions, the drainage of the fields during the wheat season is a common practice in southeastern China (Cai et al. 2002; Ju et al. 2009; Zhang et al. 2013). However, as the soil of the experimental sites in northern Jiangsu was more similar to calcareous soils of the NCP, where NH_3 volatilization losses are high and generally viewed as a major pathway for N losses (Cui et al. 2010b; Ju et al. 2009; Pacholski et al. 2006; 2008; Zhang et al. 2011), considerable NH_3 volatilization losses after surface application of urea fertilizers are most likely to occur. Leaching losses in rice-wheat systems in southeastern China are known to occur particularly from late February to the end of the winter wheat season (Cao et al. 2014), as precipitation in the beginning of the wheat season is very low and soil temperature from November to February is low as well, which delays the hydrolysis of urea and accompanying nitrification (Liang et al. 2011). In a field experiment in the Taihu Region conducted by Liang et al. (2007), NO_3^--N leaching was highly controlled by precipitation and soil type, and cumulated up to 13 % of applied N fertilizer (270 kg N ha^{-1}) on a clayey loam and up to 18 % on a silty loam. Moreover, a large part of the N applied to winter wheat can also get lost after crop harvest, when leaching and denitrification losses can be high, due to flooding of the field for the subsequent rice crop (Fan et al. 2007; Ponnamperuma 1985). Thus, fertilizer and crop management practices should follow the aim to reduce the residual N_{min} content, and NO_3^--N in particular, to a level which is as low as possible, particularly in these rice-wheat systems. Our results show, that the residual N_{min} content after the winter wheat crop is clearly affected by N fertilization and crop N uptake. The highest N_{min} contents in the soil profile were found under CN, while residual mineral N contents under RN were at a level comparable with the zero N treatment, at least from the second winter wheat season onwards. This indicates that under the current cropping practices, a further reduction of the N_{min} contents measured under RN is not possible. Higher N_{min} contents after the last wheat season were caused by the low N uptake in that season, due to particular weather conditions resulting in a high N balance surplus.

Compared to winter wheat, considerably higher N balance surpluses were calculated for summer rice crops indicating higher potential N losses to the environment under current fertilization practices during the summer rice season. Moreover, as the residual N_{min} content after rice harvest is generally low, even in years with low above-ground N uptake and high N balance surpluses (e.g. SR11), it can be assumed that most of the surplus N is lost to the environment, particularly through NH_3

volatilization and denitrification, besides leaching as NO_3^--N and DON. However, the potential for NO_3^-- and DON-leaching and run-off was relatively low on our sites, due to the high clay content and low infiltration rates of the lacustrine sediment soil in Huai'an.

The formation and emission of NH_3 is stimulated by the soil conditions (high pH and $CaCO_3$ content), the type of N fertilizer, usually urea, the climatic conditions (high temperatures and radiation can promote algal growth that can elevate floodwater pH up to 10.5 (Cai et al. 2002)) after fertilizer application, and the practice of Chinese rice farmers to broadcast the fertilizers into the ponded water of the rice fields. Direct measurements of total NH_3 emissions during the rice-growing period under conventional fertilization practices showed that NH_3 losses generally ranged between 15 and 25 % (Lin et al. 2007; Yang et al. 2013; Zhao et al. 2012b) and can reach up to 30 % of the total applied mineral N fertilizer (Fan et al. 2006). However, all of these studies were conducted in the Taihu Region, where the pH of the topsoil was usually between 5 and 7. In contrast, the soil of the experimental site in northern Jiangsu had a pH higher than 8 and a $CaCO_3$ content of > 8%, and NH_3 losses are generally higher on calcareous soils (Mikkelsen 1987; Sommer et al. 2004). The NH_3 volatilization potential may therefore be higher than that of the soils in the Taihu Region.

A significant part of the surplus N may be lost through denitrification. In a rice-wheat system in Ludhiana, India, Aulakh et al. (2001) observed direct denitrification losses by the acetylene inhibition technique during the rice season that amounted to 33 % of the applied mineral N fertilizer. Apparent denitrification losses calculated by the difference method yielded denitrification losses of 36 % of the applied mineral N fertilizer for rice-wheat systems in the Taihu Region (Ju et al. 2009) and Zhao et al. (2012b) estimated mean denitrification losses of 27 % of the applied N during the rice growing season. Up to 75 % of denitrification losses can occur during the first 6 weeks of the rice season (Aulakh et al. 2001). The applied mineral N fertilizer can also be, to some extent, immobilized through a transfer to microbial N or dissolved organic N during the rice-growing season (Reichardt et al. 2000), or through mineral NH_4^+-fixation (Nieder et al. 2011). The amounts to which these processes contribute to N transformations is hard to estimate, but in consideration of the soil properties in our experiment, it can be expected that especially NH_4^+-fixation has a considerable impact on the soil N dynamics. On the other hand, it must be considered that microbially immobilized N or minerally fixed NH_4^+ can generally be remobilized and subsequently taken up by plants or lost to the environment.

3.4.5. Crop residue management

The incorporation of crop residues had no adverse effects on plant growth, grain yield and N uptake for both crops in the first two years. This contrasts with the investigations by Verma and Bhagat (1992) who reported that straw incorporation in a rice-wheat rotation depressed grain yield of both crops in the short term compared with burning or straw removal. Moreover, grain yields and N uptake of both 'x'-treatments of SR11 were clearly increased compared to the treatments with removed wheat straw. Rice grain yield decrease due to an adverse effect of straw incorporation on young rice seedlings could not be observed. However, the incorporation of previous crops' straw led to a slightly higher N balance surplus and consequently higher N loss potential, which became apparent in the higher residual N_{min} contents in the soil after WW10/11. To avoid this, the N added via returned straw has to be considered in the fertilizer planning, as the N in crop residues contributes to the soil organic N pool and partly becomes available for the subsequent crop after mineralization (Hartmann et al. 2014). Cassman et al. (1998) reported that the N contained in rice straw had a fertilizer-N equivalent of about 85 %, when straw was incorporated in combination with mineral N fertilizer and if these N source is taken into account in the fertilizer planning, it would result in a significant reduction in total N fertilizer requirements.

Besides constituting an additional N source for the crops, proper management of cereal crop residues is extremely important to sustain soil fertility (Kundu and Ladha 1999). Declining soil organic matter (SOM) contents are a major concern in rice-upland crop rotations and straw incorporation is expected to be the only option to maintain or increase SOM in these systems (Yadvinder-Singh et al. 2005). However, with the introduction of high-yielding crop varieties and the widespread use of combine harvesters in Asian countries, a huge amount of crop residues remains in the field after harvest and farmers prefer to burn them as they hamper tillage and seeding operations for the subsequent crop (Yadvinder-Singh et al. 2005) and due to a lack of proper technology for *in situ* incorporation (Samra et al. 2003). Moreover, straw incorporation can lead to microbial immobilization of soil and fertilizer N, whereas the intensity of N immobilization and of the subsequent re-mineralization depend on the nature of plant residues and the type of decomposers (Mary et al. 1996). In our experiment, the C/N ratio of the incorporated rice straw was much lower than that of the wheat straw which implies, that the problem of N immobilization is less pronounced during the winter wheat season.

The incorporation of rice straw prior the subsequent wheat crop can easily be conducted during the preparatory tillage for the winter wheat, and hence it does not entail extra costs (Bijay-Singh et al. 2008). This was also the case in our field trials on farmers' field sites at Huai'an. The rice straw decomposes nearly totally during the wheat season and has no adverse effects on plant growth or crop establishment. Moreover, only little N immobilization and adverse effects on N availability were found if rice straw was allowed to decompose under aerobic conditions for an adequate time before sowing and fertilizer application, but at least for 10 days (Yadvinder-Singh et al. 2004). This was also found by Witt et al. (2000) who reported that early residue incorporation improved the congruence between soil N supply and crop demand and that the size of this effect was influenced by the amount and quality of incorporated residue. However, Pathak et al. (2006a) reported that grain yield would be lower if no additionally N were applied to the incorporated rice straw. Straw recycling also has a major influence on the potassium (K) balance and maintenance of soil K status of intensive rice systems (Dobermann 2007). This is of great importance in order to prevent soil K deficiency in high-yielding cereal crop rotations in China, also in view of the high price of mineral potassium fertilizer in China. Concerning the effect of different straw returning methods on trace gas emissions, Ma et al. (2010) reported that straw evenly incorporated into the topsoil reduced N_2O emissions, while mulching of rice straw increased them. Tian et al. (2001) reported that rice straw amendment to the winter wheat crop had no significant effects on NH_3 volatilization.

In contrast to the management of rice residues during the upland winter wheat crop, the management of wheat residues during irrigated lowland rice presents a considerably bigger challenge. This especially applies to the rice-wheat system in China, as there is a very short fallow period between wheat and rice and wheat straw does not have off-field value as i.e. in rice-wheat systems in India (Bijay-Singh et al. 2008). Moreover, returning and incorporation of crop residues just before the rice season stimulates CH_4 emissions strongly. In a meta-analysis from 53 sites across Asia, Yan et al. (2005) found that the most important factor controlling CH_4 emissions from rice fields were the presence or absence of organic amendments. Ma et al. (2009) reported that the evenly incorporation of wheat straw prior the rice crop increased CH_4 emissions significantly by a factor of 3.9–10.5 compared to straw removal. Additionally to the stimulation of CH_4 emissions, wheat straw incorporation effects NH_3 emissions as well. Wang et al. (2012) reported that NH_3 emissions after urea application increased by 28 % due to straw incorporation and N losses via NH_3 volatilization accounted for 21.3 % of fertilizer N. Due to the presented constraints of straw management during the flooded rice crop and the environmental impact, alternative options need to be examined. Among the most efficient alternatives range the use as substrate for mushroom cultivation, composting, biofuel production, anaerobic digestion, household combustion and other off-field uses like animal fodder, fuel, for paper mills or industrial purposes (Bakker et al. 2013; Bijay-Singh et al. 2008).

3.4.6. Recommendations related to N fertilizer application

In China, the issues of pollution and over-exploitation of farmland have come into focus more strongly recently. As a result of the implementation of the "No. 1 Central Document" released in February 2015, by the Central Committee of the Communist Party of China and the State Council, the Chinese Ministry of Agriculture (MOA) announced in March 2015 that its target would be to achieve over 40 % of fertilizer and pesticide efficiency rate in 2020, a rise of 7 % and 5 % respectively over 2013, and to achieve zero growth of fertilizer and pesticide consumption by 2020 (Ministry of Agriculture 2014). To achieve this aims, a rapid decrease of the total N fertilizer consumption is essential and sound fertilizer N recommendations for the main cropping-systems in China are required.

Based on the results from the field experiments, the agronomic indicator calculations as well as the N balance sheets, it is obvious that there is a high potential for optimizing N fertilizer management practices in the rice-wheat double-crop rotation in northern Jiangsu Province. The most important measures to reduce N surpluses and N losses to the environment are the adaption of dose and timing of fertilizer N application to the crop-specific demand. An overall reduction for the whole crop rotation of about 25 % of farmers' common fertilization practice can be achieved safely in combination with a better timing and adjustment of the split applications. However, distinctions have to be made for the two crops of the cropping system, as the reduction potential differs among them.

For winter wheat, a reduction potential of 25-30 % compared to the current farmers' practice of around 260 kg N ha^{-1} $crop^{-1}$ is assumed to be realistic, resulting in a recommended fertilizer N application rate of 180-195 kg N ha^{-1} $crop^{-1}$. Around 60 % of the diminished N amount (40-45 kg N ha^{-1}) should be reduced at basal fertilization before sowing of the wheat crop. The remaining 40 % (25-30 kg N ha^{-1}) should be reduced at same ratios for the "winter fertilization" and shooting application. The necessity for reduction is highest for the basal application, as 60 % of total fertilizer N (156 kg N ha^{-1}) is applied before sowing of the crop and N uptake during the winter season is less than 60 kg N ha^{-1}. This was reported in a similar manner for the Taihu Region (e.g. Cao et al. 2014). Moreover, in contrast to the residual N_{min} after the summer rice season in the Taihu Region, the N_{min} content found after summer rice harvest in Huai'an was considerably higher, around 50 kg N ha^{-1} (of which 40 % as NH_4^+-N) on average in our study, and can be regarded as fully available for the subsequent winter crop.

The potential to reduce N application to summer rice ranges from 20 to 25 % of the current farmers' N fertilizer application of 300 kg N ha^{-1} $crop^{-1}$, resulting in a total fertilizer N application of 225-240 kg N ha^{-1} $crop^{-1}$. The recommended N application depending on yield expectations is slightly higher than the N application under RN in our field experiments, as a slight decrease in grain yield had been observed in the third summer rice crop under RN compared to CN, albeit under a considerably lower yield level due to the abnormal weather conditions during SR11. In summary, the main reduction of fertilizer N application should focus on the early growth stages, especially during the tillering stage. Nearly 90 % of the total diminished 75 kg N ha^{-1} in our study was reduced from the split applications during early and maximum tillering stage. A similar reduction scheme was recommended for direct seeded rice in the Taihu Region by Hofmeier et al. (2015), who reduced the overall fertilizer N application by 60 kg N ha^{-1} with a share of 70 % until maximum tillering.

3.5. Conclusions

Our three-year on-farm field experiments in northern Jiangsu Province showed a considerable reduction potential for common fertilizer N application rates in the rice-wheat double-crop rotation without significant decline in mean grain yields. Recommended N application rates based on field experiments, agronomic indicators as well as the N balance sheets range between 180-195 kg N ha^{-1} $crop^{-1}$ (25-30 % reduction from current farmers' practice) to winter wheat, and 225-240 kg N ha^{-1} $crop^{-1}$ (reduction of 20-25 %) to summer rice. Emphasis of fertilizer N reduction should be placed on the basal N fertilization for winter wheat and on the N fertilization applications during tillering stage for summer rice. Compared to farmers practice, all considered agronomic indicators could significantly be increased under the 'reduced' N fertilization scheme for winter wheat, but only slightly increased for summer rice. However, reduced application rates led to a significant decrease of N surpluses of the whole double-crop rotation by 141 kg N ha^{-1} yr^{-1}, which is a clear indicator for a substantially lower N loss potential to the environment. This was supported by the net effect of fertilizer reduction on the residual mineral N content after the winter wheat crop, which is extremely exposed to get lost during field preparations for the subsequent summer rice crop. Besides the great improvement of the fertilizer N management in the rice-wheat double crop rotation, this study showed that crop residues can be incorporated easily with appropriate machinery at least to the winter wheat crop without affecting grain yields.

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4. Application of a stabilized mineral nitrogen fertilizer in the rice-wheat double-crop rotation in eastern China – Field experiment using a nitrification inhibitor

Abstract

A two-year field experiment (2009-2011) was conducted to study the effect of a nitrification inhibitor (NI) on plant growth, grain yield, nitrogen use efficiency (NUE) and mineral soil nitrogen (N) dynamics in a rice-wheat rotation in northern Jiangsu Province, China. Pure urea fertilizer and urea in combination with the NI dicyandiamide (DCD) was applied at different N application levels to winter wheat (conventional N fertilization (CN) according to the farmers' practice with 250 kg N ha^{-1}, reduced N fertilization (RN) with 180 kg N ha^{-1}, urea plus NI (U+NI-a) with 180 kg N ha^{-1}, reduced urea plus NI (U+NI-b) with 150 kg N ha^{-1}) and to summer rice (CN with 300 kg N ha^{-1}, RN with 225 kg N ha^{-1}, U+NI-a with 225 kg N ha^{-1}, U+NI-b with 200 kg N ha^{-1}) and an unfertilized control (zero N) in both crops. The number of split applications of the U+NI treatments was reduced by 1 to both crops compared to CN. The results of the experiment showed that the effect of the NI on grain yields and NUE was more pronounced in winter wheat than in summer rice. However, this was not consistent in the two observed winter wheat seasons and the efficiency of a NI under the agronomic conditions of the rice-wheat rotation is more pronounced in years with extreme weather conditions. The grain yield in the second wheat season increased significantly under U+NI-a by 26 % compared to RN and was still slightly higher than under CN. Correspondingly, the agronomic efficiency (AE_N) and the apparent recovery efficiency (RE_N) under U+NI-a increased by 26 and 45 %, respectively, compared to RN and by 36 and 47 %, respectively, compared to CN. However, the grain yield in the first winter wheat season was slightly lower under U+NI-a compared to CN and RN due to N deficiency during shooting stage and thus fertilizer application of NI treated urea during tillering should be applied depending on weather conditions and plant growth but preferably not before mid-February. A further reduction of the fertilizer N application rates below the amount applied to U+NI-a cannot be recommended, due to the slight yield decline under U+NI-b. Correspondingly to the results from the crop growth analysis, a distinct effect of the NI on mineral N dynamics in the soil were only observed during the second wheat season. For the summer rice crop, the effects of the NI on grain yield and NUE were less pronounced but we observed that the total mineral N application rate can be reduced by roughly 25 % compared to the farmers' practice independently of the use of a NI. An effect of the NI on the mineral N dynamic during the rice season could not be observed. However, a possible advantage of the application of NIs could only be derived by the potential reduction of greenhouse gas emissions from the flooded rice fields.

4.1. Introduction

The rapid transformation of agricultural production systems in China within the past three decades was accompanied by a widespread introduction and excessive use of mineral nitrogen (N) fertilizers together with new high-yielding varieties and the increased use of pesticides (Carter et al. 2012; Cui et al. 2014b). The consumption of mineral N fertilizers in China has more than tripled from the mid-1970s on (Gu et al. 2015) and the application of N fertilizer now exceeds crop N demand by far in most cropping systems (Cui et al. 2014c; Ju et al. 2009). Consequently, the N use efficiency (NUE) of mineral N fertilizers has decreased continuously (Cui et al. 2014b; Jin 2012) and high N surpluses in all major field crops led to dramatic losses of reactive N from agricultural systems to the atmosphere and to the hydrosphere. Immense eutrophication of fresh water bodies due to nitrate (NO_3^-) leaching and runoff are regularly reported (Conley et al. 2009; Gu et al. 2013; Paerl et al. 2011; Sun et al. 2012). Moreover, strongly increased emissions of ammonia (NH_3) and nitrous oxide (N_2O) after fertilizer application (Kahrl et al. 2010; Tian et al. 2012), resulting in the deposition of atmospheric N in terrestrial and aquatic ecosystems that seriously affect human and ecosystem health as well as biological diversity (Bobbink et al. 2010; Liu et al. 2011; Liu et al. 2013b). The high environmental impact due to the over-exploitation of agricultural soils have been recently become into focus more strongly and the Chinese Ministry of Agriculture (MOA) announced in 2015 that its target would be to achieve a fertilizer efficiency rate of more than 40 % and a zero growth of fertilizers and pesticides until 2020 (MOA 2015).

One of the most intensive cropping systems in China is the double-crop rotation of irrigated summer rice (*Oryza sativa* L.) and a winter upland crop, mainly winter wheat (*Triticum aestivum* L.) or oilseed rape (*Brassica napus* L.). High mineral fertilizer N application rates of up to 550 kg N ha^{-1} yr^{-1} for one crop rotation are common and low NUE due to the fertilizer application by far exceeding the crop N demand, have often been reported (Fan et al. 2013; Ju et al. 2009; Peng et al. 2006). As a consequence, the N balance surplus and thus the N loss potential of this high intensive cropping system can be as high as 350 kg N ha^{-1} yr^{-1} (Ju et al. 2009). The major N loss pathways are denitrification and NH_3 volatilization during the summer rice season and denitrification and NO_3^- leaching during the winter wheat season.

Many mitigation strategies to increase NUE and to reduce N balance surpluses in the rice-wheat crop rotation consists, focusing on the overall reduction of fertilizer N application rates. However, N losses can also efficiently be reduced by the optimization of fertilization practices with regard to timing and N amount (fertilizer application according to crop demand, Dobermann et al. 2004), type of fertilizer (i.e. replacement of urea fertilizer by other N fertilizers that have a lower N loss potential, Youngdahl et al. 1986, Stehfest and Bouwman 2006) or by the stabilization of applied fertilizer-N from ammonium-based or urea fertilizers. The stabilization can be achieved by techniques to bring the fertilizer-N under the soil surface (i.e. deep placement, fertilizer incorporation, Roger et al. 1980, Rees et al. 1996, Mohanty et al. 1998), by the sub-surface application of high concentrated ammonium containing fertilizers (Sommer et al. 2004) or by the amendment of ammonia-based or urea fertilizers with a nitrification inhibitor (NI). The use of NIs such as dicyandiamide (DCD) or 3,4-dimethylpyrazole-phosphate (DMPP) slow down the nitrification process by inhibiting the activities of *Nitrosomonas* bacteria. They delay the transformation of NH_4^+ to NO_2^- und thus, the formation of NO_3^-, that have a much greater potential to be leached beyond the rooting zone compared to NH_4^+ (Prasad and Power 1995; Subbarao et al. 2006). Moreover, N_2O emissions originating directly from the nitrification process and from the denitrification of NO_3^- can be efficiently reduced (Akiyama et al. 2010; Ruser and Schulz 2015; Weiske et al. 2001). As these N losses lower the efficiency of applied N fertilizers, the use of NIs can increase NUE by increasing plant growth and N uptake, assuming enhanced utilization capacity for the preserved N in soil (Abalos et al. 2014; Liu et al. 2013a).

To determine the mitigation potential of urea in combination with a NI in the rice-wheat double-cropping system in northern Jiangsu Province in eastern China, a static field experiment was established and the suitability of a NI (a mixture of dicyandiamide (DCD) and 1*H*-1,2,4-triazol) was tested over two consecutive double crop rotations. The objectives of this study are to investigate whether (1) higher grain yields can be achieved with NIs under the currently recommended N application rates for rice and wheat, (2) similar grain yields can be achieved with NIs and a reduction of the recommended N fertilizer rate, (3) fertilizer NUEs can be increased and N losses reduced by adding NI, (4) labour can be saved by reducing the number of split applications, and (5) to observe the impact of the NI on soil mineral N contents and dynamics during rice and wheat seasons.

4.2. Material and Methods

4.2.1. Experimental site

The field experiment was conducted on a farmers' field near Lingqiao village, Huai'an county, northern Jiangsu Province, China (33°35'N, 118°53'E) from July 2009 to June 2011. The most important farming system of the study region is the double-crop rotation of irrigated summer rice between early July and late October and upland winter wheat from early November to early June. The experimental site was directly adjacent to field experiments on farmers' field plots for demonstration purposes (to be published separately). The soil of the study site has developed from lacustrine sediments and was classified as an Anthraquic Cambisol according to IUSS Working Group WRB (2007). The texture was categorized as silty clay in the topsoil (0-0.2 m) and as silty clay loam in the subsoil (Table 4.1). The topsoil had an organic carbon (C) content of 1.8 % and a total N content of 0.22 %. The soil pH (H_2O) was moderately alkaline at 8.3. The available potassium (K) and phosphorous (P) contents were classified as moderate and very low, respectively. The $CaCO_3$ content throughout the 0-0.9 m soil profile ranged from 8.2 to 9 %.

Table 4.1: Major soil characteristics of the experimental field in Huai'an.

Depth	**pH**	**$CaCO_3$**	**SOC**	**N_{tot}**	**Av. K**	**Av. P**	**CEC**	**Bulk density**	**Sand[a]**	**Silt**	**Clay**
(cm)	(H_2O)	(%)	(%)	(%)	(mg kg^{-1})	(mg kg^{-1})	(cmol kg^{-1})	(g cm3)	(%)	(%)	(%)
0-20	8.3	8.9	1.8	0.22	215	13.2	22.2	1.29	1.8	53.5	44.8
20-60	8.4	9.0	1.0	0.08	160	2.1	18.2	1.5	11.5	57.7	30.8
60-90	8.4	8.2	0.7	0.08	158	3.5	17.5	1.23	0.9	70.4	28.8

[a] Sand: 2-0.063 mm; Silt: 0.063-0.002 mm; Clay: < 0.002 mm

The study region had a warm temperate climate with summer monsoon rainfall. Mean temperature and precipitation at the study site was 14.6°C and 992 mm (1957 to 2011), respectively, with only 30 % of the total precipitation occurring between November and May (Figure 4.1).

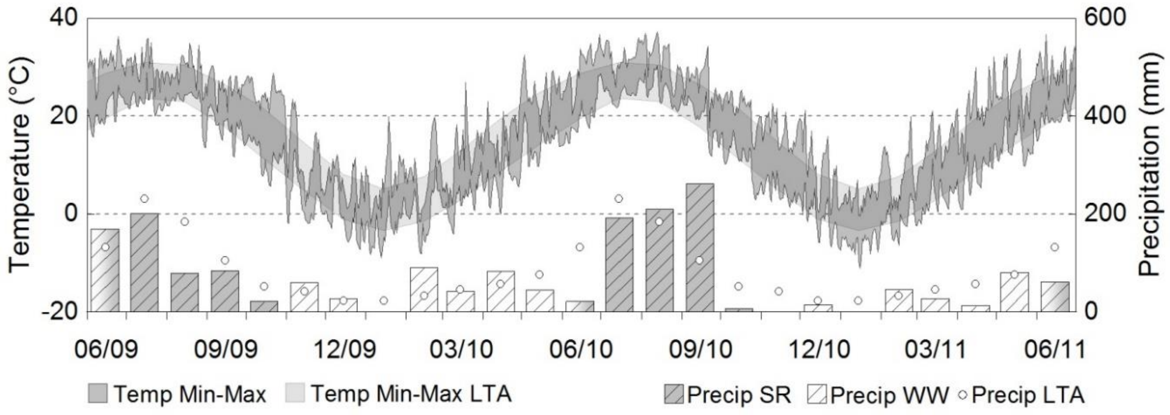

Figure 4.1: Precipitation (cumulative monthly rainfall during field experiment and long-term average (LTA)) and temperature (daily min and max during field experiment and LTA of min and max) during the two summer rice (SR)-winter wheat (WW) rotations (June 2009 - June 2011) in Huai'an, China.

4.2.2. Experimental design

A two-year static field experiment was established for two consecutive summer rice-winter wheat double-crop rotations, starting in July 2009 with the summer rice crop and ending in May 2011 after the second winter wheat season. An unfertilized control (zero N) and three different N fertilization treatments were tested with four replicates in a completely randomized latin square design. Each experimental plot was approx. 80 m^2 in size and lay adjacent to an irrigation canal to maintain a plot-specific irrigation management. The plots were surrounded by ridges (40 cm in height) in order to prevent an exchange of ponded water and dissolved fertilizer between canal and plot during the summer rice season.

Detailed information on fertilizer N treatments is listed in Table 4.2 (summer rice) and

Table 4.3 (winter wheat). The conventional N treatment (CN) was fertilized with pure urea according to the farmers´ fertilization practice for both crops, except for the first rice season when N fertilization to CN was reduced by 25 %. Two treatments (U+NI-a and U+NI-b) were fertilized with urea in combination with the nitrification inhibitor dicyandiamide (DCD) and 1H-1,2,4-triazol (commercially available as ALZON® 46). Compared to the farmers' fertilization practice, fertilizer N application rates for the U+NI-a treatment were 25 and 28 % lower to rice and wheat, respectively, and the number of split applications to both crops was reduced by one. For the U+NI-b treatment, the number of split applications was similar to U+NI-a but compared with this, the N application rate was further reduced by 17 and 11 % for wheat and rice, respectively. Additionally, a 'reduced urea' treatment (RN) from a directly adjacent on-farm demonstration experiment (to be published separately) with five replicated plots was included in the evaluation. Mineral N fertilizer for RN was applied as pure urea and the N amount was similar to the U+NI-a treatment. Except for the first rice season, when the transplanted rice seedlings were more evenly distributed and separately pushed into the soil, field and crop management in the static and the adjacent demonstration experiment were identical. All fertilizers were surface-broadcasted by hand and only basal fertilizer applications were incorporated into the soil.

Table 4.2: Fertilizer application rates to the summer rice crops 2009 and 2010 in the field experiment in Huai'an.

Treatment	**Split applications**	**N appl.**	**Transplanting**	**Early tillering**	**Maximum tillering**	**Panicle initiation**	**Booting**
	(n)	(kg N ha^{-1})	(kg NPK ha^{-1})	(kg N ha^{-1})	(kg N ha^{-1})	(kg NK ha^{-1})	(kg N ha^{-1})
CN	4 / 4 [a]	225 / 300	45 NPK	75 / 110 urea	- / 45 urea	75 / 100 urea + 22.5 KCl	30 / - urea
RN	4 / 3	225 / 225	45 NPK	75 / 90 urea	-	75 / 90 urea + 22.5 KCl	30 / - urea
U+NI-a	3 / 3	225	45 NPK	90 U+NI	-	90 U+NI + 22.5 KCl	-
U+NI-b	3 / 3	200	45 NPK	75 U+NI	-	80 U+NI + 22.5 KCl	-
zero N	-	-	45 TSP + 45 KCl	-	-	22.5 KCl	-

Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization treatment from adjacent demonstration experiment; U+NI-a - application of a NI with reduced split applications but N amount similar to RN; U+NI-b - application of a NI with reduced split applications and reduced N amount compared to RN; zero N - unfertilized control without N application; NPK – NPK compound fertilizer; U – urea; NI – nitrification inhibitor; TSP – triple superphosphate.
[a] split applications and nutrient amount of CN and RN in SR09 / SR10.

Table 4.3: Fertilizer application rates to the winter wheat crops 2009/10 and 2010/11 in the field experiment in Huai'an.

Treatment	**Split applications**	**N appl.**	**Basal fertilization**	**Tillering**	**Shooting**
	(n)	(kg N ha^{-1})	(kg NPK ha^{-1})	(kg NK ha^{-1})	(kg N ha^{-1})
CN	3	250	90 urea + 56 NPK	52 urea	52 urea
RN	3	180	54 urea + 56 NPK	35 urea	35 urea
U+NI-a	2	180	80 U+NI + 56 TSP + 56 KCl	100 U+NI	-
U+NI-b	2	150	70 U+NI + 56 TSP + 56 KCl	80 U+NI	-
zero N	-	-	56 TSP + 56 KCl	-	-

Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization treatment from adjacent demonstration experiment; U+NI-a - application of a NI with reduced split applications but N amount similar to RN; U+NI-b - application of a NI with reduced split applications and reduced N amount compared to RN; zero N - unfertilized control without N application; NPK – NPK compound fertilizer; U – urea; NI – nitrification inhibitor; TSP – triple superphosphate.

4.2.3. Crop management

All crop management practices except for the fertilizer N application were carried out by the local farmers according to their common practice. Field preparation for the summer rice crop (SR; cv. *lian geng* 6#) was performed by puddling the topsoil and levelling the fields to maintain a uniform water level in the fields. For basal application, NPK compound fertilizer (45 kg ha^{-1} as pure nutrients) was broadcasted by hand to the N fertilization treatments, while zero N plots received 45 kg P_2O_5 ha^{-1} as triple superphosphate and 45 kg K_2O ha^{-1} as KCl. Subsequently, 21 days old rice seedlings were transplanted manually by uniformly throwing the hills (about 3 seedlings per hill with a planting density of 45 hills m^{-2}) into the levelled field. Water level was maintained between 5-10 cm and fields were drained for mid-term aeration before panicle initiation in August. After re-flooding the fields, all plots received another 22.5 kg K_2O ha^{-1} at booting fertilization. About 4 weeks before maturity, plots were drained again and rice plants were harvested and threshed manually in late October.

Before sowing the subsequent wheat crop, a basal application of NPK compound fertilizer (56 kg ha^{-1} as pure nutrients) and additionally urea fertilizer was uniformly broadcasted by hand to the N fertilizer treatments and the zero N plots received a corresponding amount of triple superphosphate and KCl. Rice stubbles and fertilizer were then incorporated with a rotary tiller to prepare the seed bed. After field preparation, winter wheat (WW; cv. *huai mai* 20#) was sown by hand with a mean seeding rate of 280 kg seeds ha^{-1} and slightly incorporated into the soil with a rotary tiller. Winter wheat was harvested and threshed by hand in late May/early June.

4.2.4. Yield determination and plant analyses

Grain yields of rice and wheat were determined at maturity through weighing all threshed grains at the nearby experimental station. For determination of the grain moisture content, grain sub-samples were taken directly after threshing and oven-dried at 80°C until constant weight was reached. Grain yields are reported with a standardized water content of 14 %. In order to determine straw yield, yield components and plant C and N contents, plant samples were taken directly before harvest and separated into stem, leaves and panicles/ears. All sub-samples were pre-dried for 1 h at 105°C followed by drying at 80°C for 48 h. Dry weights of plant parts and yield components were determined. Plant parts were ground for the subsequent analyses of C and N contents through high-temperature combustion followed by gas analysis (Vario Max CN, Elementar Analysensysteme GmbH, Hanau, Germany). The above-ground N uptake was calculated by multiplying the determined N contents with the dry matter of the respective separated plant parts.

4.2.5. Soil analyses

Mineral N contents (N_{min} = NO_3^--N + NH_4^+-N) were determined separately for 0-0.2, 0.2-0.6 and 0.6-0.9 m soil depth increments directly after harvest of winter wheat and summer rice crops (residual N_{min}) and before each fertilizer N application during the winter wheat season. Four replicate soil cores were taken randomly from each plot with an auger, and bulked for each depth increment. Field-moist soil samples were kept cool during transport and stored at 4°C until extraction. Samples were homogenized and extracted within one day by shaking for 1 h with 1 M KCl at a soil:solution ratio of 1:4. Soil extracts were analyzed for NO_3^--N and NH_4^+-N with a continuous-flow auto analyzer (SKALAR, San Plus System, Breda, The Netherlands). For the conversion of N_{min} contents to an area basis (kg N ha^{-1}), actual soil bulk densities were used.

For the determination of mineral N contents in the soil during the summer rice season, soil and soil solution samples were taken only from the waterlogged puddled layer (0-0.2 m) with a plastic tube of 20 cm length and 5 cm diameter. Samples were taken every second day up to 10 days following each fertilizer application. Wet soil samples were first centrifuged followed by an extraction of the remaining soil with 2 M KCl at a soil:solution ratio of 1:4. The centrifuged soil solution and the soil extract were analyzed for NO_3^--N and NH_4^+-N, while the soil solution was additionally analyzed for dissolved organic N (DON).

4.2.6. Agronomic indicators

Several indicators for NUEs and the effect of N fertilization on grain yields were determined. Agronomic indices used for the estimation of NUEs included apparent recovery efficiency (RE_N) and agronomic efficiency (AE_N) of applied N. These efficiencies were calculated based on the difference between N uptake in above-ground biomass and crop yields between fertilized plots and an unfertilized control, as described by Craswell and Godwin (1984). The RE_N expresses the uptake efficiency of fertilizer N, while the AE_N describes the yield increase per unit fertilizer applied. Additionally, to indicate the effect of N fertilization on grain yield, the partial productivity of N fertilization (PFP_N) was used. The indicators were calculated as follows:

$RE_N = (U_N - U_0) / F_N$ (kg kg^{-1}),

$AE_N = (Y_N - Y_0) / F_N$ (kg kg^{-1}),

$PFP_N = Y_N / F_N$ (kg kg^{-1}),

with Y_N and Y_0 as the grain yields (Mg ha^{-1}) with and without fertilizer N input, U_N and U_0 as the total N uptake (kg N ha^{-1}) in above-ground biomass at physiological maturity with and without N input, and F_N as the amount of applied N fertilizer (kg N ha^{-1}).

4.2.7. Statistical analyses

Statistical analyses were performed using OriginPro Software (OriginLab, Northampton, MA). The differences in grain yields, above-ground N uptake and agronomic indicators as well as N_{min} contents between the treatments were analyzed for statistical significance by an ANOVA. Differences were tested for significance using Tukey's range test.

4.3. Results

4.3.1. Grain yield

A distinct effect of fertilizer N application was observed in both summer rice seasons. Grain yields in SR09 and SR10 under CN were 9.18 and 7.11 Mg ha^{-1}, respectively, compared to 4.06 and 4.47 Mg ha^{-1} on the zero N plots (Table 4.4). Grain yields were considerably lower in SR10 compared to SR09, except for zero N. However, due to heavy lodging in all CN plots directly before harvest in 2010, the lower yield level was distinctly pronounced under CN in SR10. Compared to CN, the grain yield in SR09 was slightly higher under U+NI-a (*n.s.*) but lower under U+NI-b (n.s.). The results from RN in SR09 are only comparable to a limited extent with results from the other treatments as the crop management was less intensive during that season in the demonstration field experiment which led to a poorer crop stand and a patchier crop. In SR10, grain yields of both U+NI treatments and of RN were not affected by lodging and were higher (*n.s.*) compared to yields under CN.

Table 4.4: Grain yield, N uptake and indices of nitrogen use efficiency for the summer rice seasons 2009 to 2010 in Huai'an.

Year	**Treatment**	**Grain yield** (Mg ha^{-1})	**N uptake** (kg N ha^{-1})	**PFP$_N$** (kg kg^{-1})	**AE$_N$** (kg kg^{-1})	**RE$_N$** (kg kg^{-1})
SR09	CN	9.18 ± 0.35 ab	166 ± 4 b	40.8 ± 1.6 ab	22.7 ± 1.6 ab	0.45 ± 0.02 b
	RN [a]	8.30 ± 0.53 b	164 ± 6 b	36.9 ± 2.4 b	18.8 ± 2.4 b	0.44 ± 0.02 b
	U+NI-a	9.44 ± 0.30 a	186 ± 13 a	41.9 ± 1.4 a	23.9 ± 1.4 a	0.54 ± 0.06 a
	U+NI-b	8.92 ± 0.55 ab	153 ± 6 b	44.6 ± 2.8 a	24.3 ± 2.8 a	0.44 ± 0.03 b
	zero N	4.06 ± 0.62 c	65 ± 8 c			
SR10	CN	7.11 ± 0.16 a	139 ± 5 a	23.7 ± 0.5 b	8.8 ± 0.5 b	0.27 ± 0.01 b
	RN	8.00 ± 0.10 a	144 ± 6 a	35.6 ± 0.5 a	15.7 ± 0.5 a	0.38 ± 0.02 a
	U+NI-a	8.11 ± 0.69 a	153 ± 13 a	36.0 ± 3.1 a	16.2 ± 3.1 a	0.42 ± 0.05 a
	U+NI-b	7.96 ± 1.15 a	140 ± 18 a	39.8 ± 5.8 a	17.5 ± 5.8 a	0.41 ± 0.08 a
	zero N	4.47 ± 0.33 b	58 ± 9 b			

Means followed by different letters were significantly different at $P < 0.05$.
Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization treatment from adjacent demonstration experiment; U+NI-a - application of a NI with reduced split applications but N amount similar to RN; U+NI-b - application of a NI with reduced split applications and reduced N amount compared to RN; zero N - unfertilized control without N application; PFP$_N$ - partial factor productivity; AE$_N$ - agronomic efficiency; RE$_N$ - apparent recovery efficiency.
[a] results from RN in SR09 are only comparable to a limited extent with results from the other treatments.

In both winter wheat seasons, the yield of all N treatments were significantly higher than in the respective zero N (Table 4.5). Grain yields of the N treatments in WW09/10 were highest under CN but the difference was only significant ($P < 0.05$) compared to U+NI-b. Yields under U+NI-a and RN were on a similar level with the grain yield under CN. Compared to WW09/10, grain yields were considerably lower in all treatments in WW10/11 when temperatures were very low and there was nearly no precipitation during the winter months (Figure 4.1). The highest yields in WW10/11 were observed under U+NI-a. Yields were significant higher (*P* < 0.05) compared to RN and slightly higher compared to CN and U+NI-b (*n.s.*).

Table 4.5: Grain yield, N uptake and indices of nitrogen use efficiency for the winter wheat seasons 2009/10 and 2010/11 in Huai'an.

Year	**Treatment**	**Grain yield**	**N uptake**	**PFP_N**	**AE_N**	**RE_N**
		(Mg ha^{-1})	(kg N ha^{-1})	(kg kg^{-1})	(kg kg^{-1})	(kg kg^{-1})
WW09/10	CN	7.41 ± 0.41 a	174 ± 17 a	29.6 ± 1.6 c	18.7 ± 1.6 b	0.52 ± 0.06 a
	RN	6.86 ± 0.44 ab	146 ± 10 b	39.7 ± 2.5 ab	23.9 ± 2.5 a	0.58 ± 0.05 a
	U+NI-a	6.78 ± 0.46 ab	148 ± 16 b	37.7 ± 2.5 b	22.5 ± 2.5 ab	0.57 ± 0.08 a
	U+NI-b	6.38 ± 0.19 b	127 ± 9 b	42.5 ± 1.3 a	24.4 ± 1.3 a	0.55 ± 0.05 a
	zero N	2.72 ± 0.15 c	45 ± 4 c			
WW10/11	CN	5.79 ± 0.88 ab	134 ± 18 a	23.2 ± 3.5 b	17.8 ± 3.5 b	0.44 ± 0.06 b
	RN	4.82 ± 0.56 b	118 ± 11 a	26.8 ± 3.1 b	19.3 ± 3.1 b	0.52 ± 0.06 ab
	U+NI-a	6.06 ± 0.39 a	130 ± 10 a	33.7 ± 2.1 a	26.2 ± 2.1 a	0.59 ± 0.05 ab
	U+NI-b	5.81 ± 0.33 ab	119 ± 14 a	38.8 ± 2.2 a	29.8 ± 2.2 a	0.63 ± 0.08 a
	zero N	1.34 ± 0.35 c	24 ± 5 b			

Means followed by different letters were significantly different at P < 0.05.
Abbreviations: CN - conventional N fertilization; RN - reduced N fertilization treatment from adjacent demonstration experiment; U+NI-a - application of a NI with reduced split applications but N amount similar to RN; U+NI-b - application of a NI with reduced split applications and reduced N amount compared to RN; zero N - unfertilized control without N application; PFP_N - partial factor productivity; AE_N - agronomic efficiency; RE_N - apparent recovery efficiency.

4.3.2. Yield components

Panicle number of summer rice increased significantly (*P* < 0.05) with N application compared to zero N, but there were no significant differences between the different N treatments in both years (Figure 4.2a). However, treatments with high grain yields had a slightly increased panicle number (CN and U+NI-a in SR09 and U+NI treatments in SR10). Filled grains per spikelet and the 1,000-grain weight (TGW) were not affected by differences in N rates and source in both years. However, significantly (*P* < 0.05) more filled spikelets per panicle were observed under zero N treatments compared to the N fertilized treatments, except for U+NI-b in SR10. The TGW of the N treatments did not differ from the zero N treatment.

In WW09/10, the ear number was significantly higher (*P* < 0.05) under CN compared to RN and zero N (Figure 4.2b). The ear numbers of U+NI treatments were lower than under CN (*n.s.*) but higher compared to RN (*n.s.*) and zero N (*P* < 0.05). In WW10/11, a similar trend was observed with comparable ear numbers under CN, U+NI-a and U+NI-b, and significantly lower (*P* < 0.05) ear numbers under RN and zero N. Spikelet number of all N treatments were significantly higher (*P* < 0.05) compared to zero N in both wheat seasons and did not differ between each other. Highest TGW in WW09/10 was observed under zero N, which was significantly (*P* < 0.05) higher than TGW of CN. The TGW under RN and the U+NI treatments ranged between CN and zero N. In WW10/11, when grain yields were low, the trend of TGW was different. The significantly highest TGW was then observed under RN ($P < 0.05$) and did vary only slightly among the other treatments.

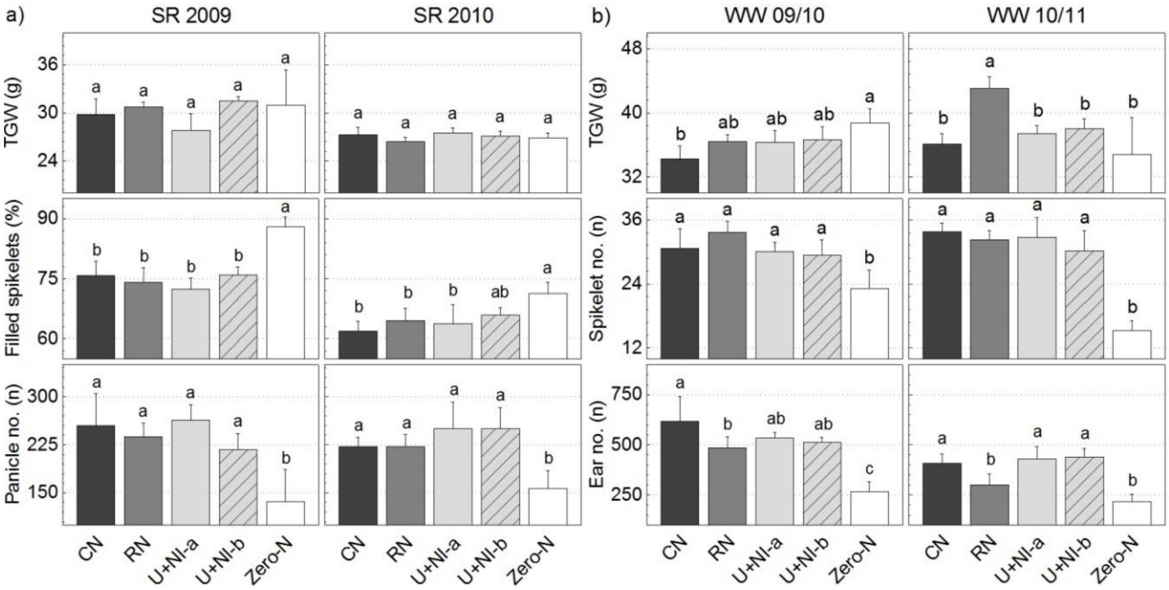

Figure 4.2: Yield components of summer rice (SR) (a) and winter wheat (WW) (b) crops in Huai'an, China (bars: mean values; error bars: ± s.d.; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN); TGW = 1,000-grain weight; results from RN in SR09 are only comparable to a limited extent with results from the other treatments).

4.3.3. Nitrogen uptake

Mean above-ground N uptake was highest under U+NI-a in both summer rice seasons (Table 4.4). The difference to the other N treatments was significant ($P < 0.05$) in SR09. The higher N uptake under U+NI-a in SR09 corresponded well with the higher grain yields under that treatment. The lowest N uptake among the N treatments in SR09 was observed under U+NI-b (*n.s.*). Despite a lower grain yield under RN compared to the other N treatments in SR09, the N uptake of RN was comparable to CN and even slightly higher than in U+NI-b in that year. The N uptake under zero N was significantly lower ($P < 0.05$) than under the N treatments in both rice seasons.

Nitrogen uptake by winter wheat was highest under CN in both wheat seasons. Compared to the other N treatments, this difference was significant ($P < 0.05$) in WW09/10 when the N uptake of the other N treatments did not differ between each other (Table 4.5). However, it has to be noted, that there was a trend to lower N uptake under U+NI-b in WW09/10, which corresponds to the lower grain yield of this treatment. In WW10/11, the differences in N uptake among the N treatments were not significant. However, N uptake was slightly lower under RN and U+NI-b (*n.s.*) compared to CN and U+NI-a. As for the rice seasons, mean above-ground N uptake was lowest under zero N and extremely low in WW10/11.

4.3.4. Agronomic indicators

In the first summer rice season (SR09), the mean PFP_N and AE_N were higher in the U+NI treatments compared to CN (n.s.) and RN ($P < 0.05$) (Table 4.4). No differences were found between the calculated RE_N under CN, RN and U+NI-b. In contrast, the RE_N under U+NI-a was significantly higher ($P < 0.05$) by 22 % compared to the other three N treatments. In SR10, all calculated agronomic indicators were significantly lower ($P < 0.05$) under CN than all other treatments. The PFP_N, AE_N and RE_N under RN and the U+NI treatments were 50-67 %, 78-99 % and 41-56 % higher, respectively, compared to CN.

In both winter wheat seasons, all three agronomic indicators were lowest under CN (Table 4.5). In WW09/10, the PFP_N under CN was significantly lower ($P < 0.05$) compared to the other N treatments and the AE_N was significantly lower ($P < 0.05$) compared to RN and U+NI-b. The difference in the RE_N was very small among the treatments (*n.s.*). In WW10/11, the PFP_N and the AE_N were significantly ($P < 0.05$) higher in the U+NI-a and U+NI-b treatments compared to CN and RN with the highest values under U+NI-b. Higher values of the U+NI-a and U+NI-b treatments were also found for the RE_N compared to CN (*n.s.* and $P < 0.05$, respectively) and RN (both *n.s.*).

4.3.5. Residual mineral N at harvest

The initial soil N_{min} content in 0-0.9 m soil depth of the whole experimental plot after harvest of the preceding winter wheat crop (2008/09) and before field preparation for the first summer rice crop (SR09) was 39 kg N ha^{-1} (data not presented here). Total fertilizer N application to the previous crop was 180 kg N ha^{-1} (similar to RN). Residual N_{min} contents after SR09 and SR10 showed no clear differentiation between the treatments (Figure 4.3) and ranged from 50 to 80 kg N ha^{-1}. The portion of NH_4^+-N in total residual N_{min} was higher than NO_3^--N (62 % NH_4^+-N on average) in all treatments after SR09 while slightly more NO_3^--N compared to NH_4^+-N was found under CN (60 % NO_3^--N) and RN (82 % NO_3^--N) after SR10.

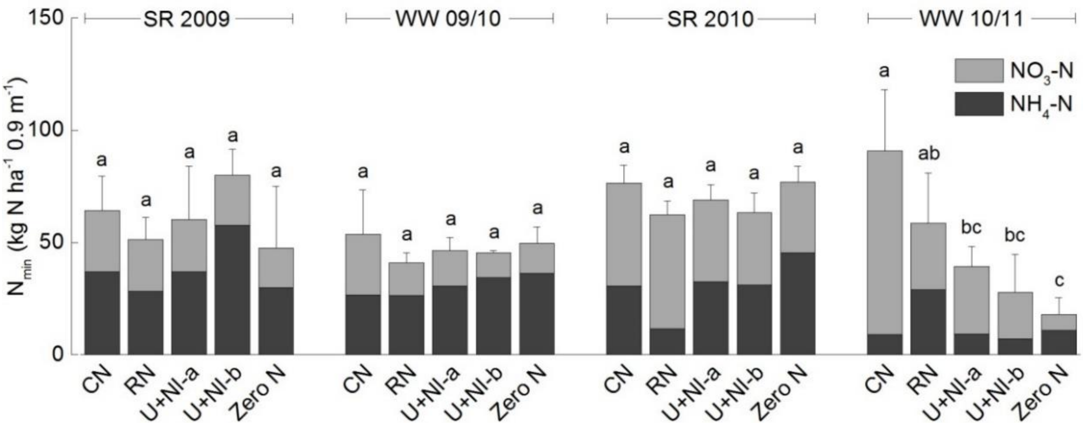

Figure 4.3: Mean residual N_{min} (NO_3^--N and NH_4^+-N) contents in 0-0.9 m soil depth after harvest of summer rice and winter wheat crops in Huai'an, China (bars: mean values; error bars: ± s.d., n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment).

The mineral N contents after the winter wheat harvest of WW09/10 showed no differentiation between the treatments (Figure 4.3). The mean N_{min} content of all treatments after WW09/10 was 47 kg N ha^{-1} (ranging from 41 kg N ha^{-1} under RN to 54 kg N ha^{-1} under CN), with a higher portion of NO_3^--N in total N_{min} under CN (51 % or 27 kg NO_3^--N ha^{-1}) compared to the other treatments (24-35 % or 11-16 kg NO_3^--N ha^{-1}). Significantly higher N_{min} contents ($P < 0.05$) were observed in WW10/11 under CN compared to U+NI-a (1.3-fold higher) and U+NI-b (2.4-fold higher) treatments and zero N (4.1-fold higher). Under CN, 82 kg NO_3^--N ha^{-1} was observed in the profile (90 % of the total N_{min}) while it was 7 to 31 kg NO_3^--N ha^{-1} in the other treatments.

4.3.6. Time course of mineral N during the summer rice season

The time course of NH_4^+-N, extracted from the puddled soil layer, showed no differences between the N treatments during the whole rice season SR09 (Figure 4.4a). Average NH_4^+-N contents ranged from 5 to 15 mg NH_4^+-N kg^{-1} until the first top dressing at early tillering (8 days after transplanting, DAT), from 20 to 35 mg NH_4^+-N kg^{-1} until the second top dressing at maximum tillering (16 DAT) and from 4 to 18 mg NH_4^+-N kg^{-1} until panicle initiation (47 DAT), with two exceptions for RN at 49 and 53 DAT. Ammonium contents under zero N were significantly lower ($P < 0.05$) compared to the N treatments during the tillering stage and ranged from 3 to 11 mg NH_4^+-N kg^{-1} during the whole rice season. The time courses of NH_4^+-N concentrations in the soil solution were similar to the courses of extracted NH_4^+-N and ranged from 0.5 to 3.6 mg NH_4^+-N l^{-1} (Figure A.1a). No differences were observed between the treatments (incl. zero N) in the time courses of DON during SR09 (Figure A.2a).

Compared to SR09, the NH_4^+-N contents in the puddled soil layer of the N treatments were considerably higher during SR10 (Figure 4.4b). Average NH_4^+-N contents between basal fertilization and first top dressing at early tillering ranged from 17 to 41 mg NH_4^+-N kg^{-1}, without any significant differences between the N treatments. Different time courses of extracted NH_4^+-N between the urea treatments and the U+NI treatments were observed after the first top dressing, with higher NH_4^+-N contents under CN and RN (*n.s.*) until 15 DAT. However, the NH_4^+-N content under U+NI-b were higher (*n.s.*) compared to CN and RN at 18 DAT. Ammonia contents under CN increased again after the second top dressing at 18 DAT to 62-71 mg NH_4^+-N kg^{-1}. As no fertilizer was applied to U+NI treatments and RN at 18 DAT, no soil samples were taken at 20 and 22 DAT. After the third top dressing at panicle initiation, the NH_4^+-N contents increased with slightly higher values under CN and U+NI-a at 52 DAT and the NH_4^+-N content under U+NI-a did not change till 54 DAT. Ammonium contents under zero N during SR10, ranging from 3 to 13 mg NH_4^+-N kg^{-1} and were significantly ($P < 0.05$) lower compared to the N treatments during all growth stages and comparable to those in SR09. Also during SR10, the time courses of NH_4^+-N concentrations in the soil solution of the N treatments were similar to the contents of extracted NH_4^+-N, and ranged from 0.8 to 4.2 mg NH_4^+-N l^{-1} during tillering stage and from 0 to 2.3 mg NH_4^+-N l^{-1} after panicle initiation (Figure A.1b). Ammonium concentrations in soil solution under zero N were lower compared to SR09 and decreased to values below the detection limit from DAT 21 onwards. No differences between the treatments were observed in the time courses of DON during SR10 (Figure A.2b), except for the sharp increase of DON at 12 DAT in all N treatments.

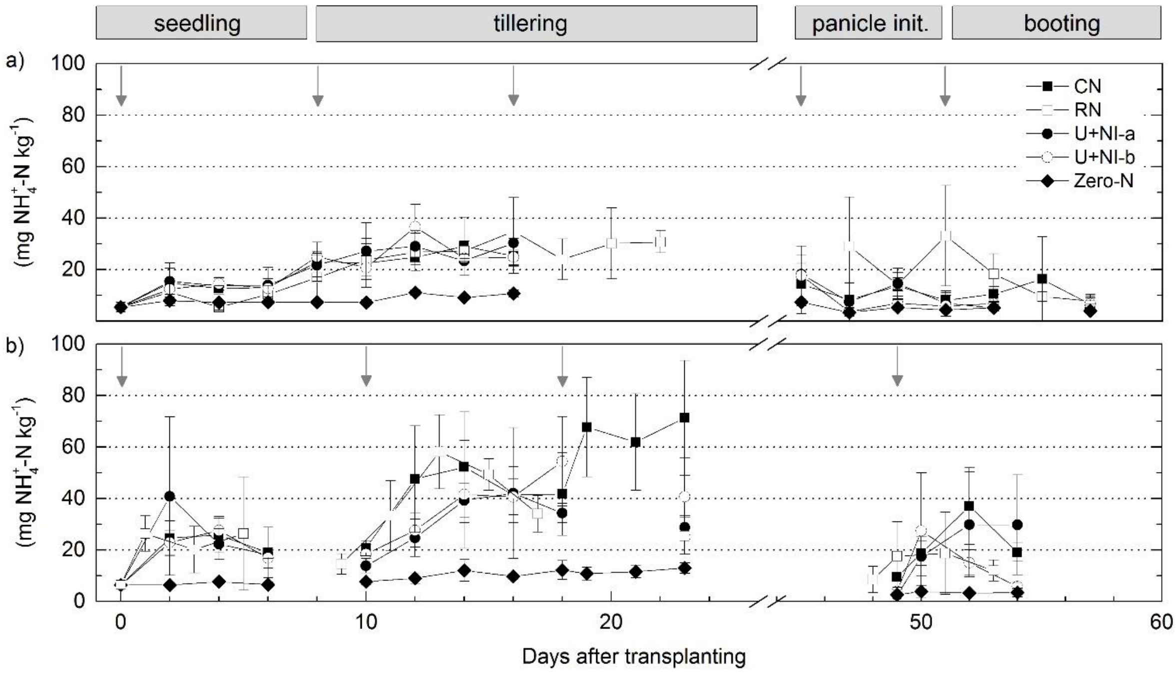

Figure 4.4: Time course of mean NH_4^+-N contents in soil KCl extracts expressed as mg NH_4^+-N per kg soil of puddled layer (0-0.2 m) during summer rice season 2009 (a) and 2010 (b) in Huai'an, China (error bars: ± s.d.; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment; arrows indicate fertilizer application events; crop growth stages are shown at the top).

4.3.7. Mineral N profiles during the winter wheat season

The N_{min} contents in the 0-0.9 m soil profiles before shooting fertilization in March were very different between WW09/10 and WW10/11 (Figure 4.5). Generally, N_{min} contents in the N treatments were much lower in WW09/10 compared to WW10/11 while N_{min} contents under zero N did not differ between the two seasons. In WW09/10, N_{min} contents under CN were significantly higher ($P < 0.05$) compared to U+NI-b and zero N and N_{min} contents under RN and U+NI-a were similar and significantly higher ($P < 0.05$) compared to zero N. However, in the first wheat season (WW09/10), 34 and 27 % of total N_{min} were still in the 0-0.2 m increment under U+NI-a and U+NI-b, respectively, and comparatively smaller portions were found in the topsoil under CN and RN with 23 and 19 % of total N_{min}, respectively. In WW10/11, the portions of the topsoil-N_{min} among the total N_{min} contents of the whole profile were 63, 51, 66 and 71 % under CN, RN, U+NI-a and U+NI-b, respectively. Significantly higher portions ($P < 0.05$) were found in the U+NI treatments compared to RN. Moreover, more than half of the total N_{min} content in the topsoil of the U+NI treatments were NH_4^+-N with 56 and 62 % NH_4^+-N, respectively. These portions were significantly higher ($P < 0.05$) compared to CN and RN, where only 7 % of the total topsoil-N_{min} was NH_4^+-N.

The N_{min} contents in the soil profiles after wheat harvest in June (Figure 4.6) were clearly lower compared to the N_{min} contents in March. After WW09/10, the portion of the topsoil-N_{min} among the total N_{min} content was similar between the treatments and ranged from 30 % under zero N to 40 % under CN. Furthermore, the portion of NO_3^--N among the topsoil-N_{min} was highest under CN (76 % NO_3^--N) and lowest under U+NI-b (50 % NO_3^--N). Considerably higher portions of N_{min} in the topsoil were found after the wheat harvest in WW10/11. They accounted for 54, 44, 69 and 66 % of total N_{min} under CN, RN, U+NI-a and U+NI-b, respectively. Nearly all of the topsoil-N_{min} was NO_3^--N with the highest portion under CN (97 % NO_3^--N) and the lowest under RN (80 % NO_3^--N).

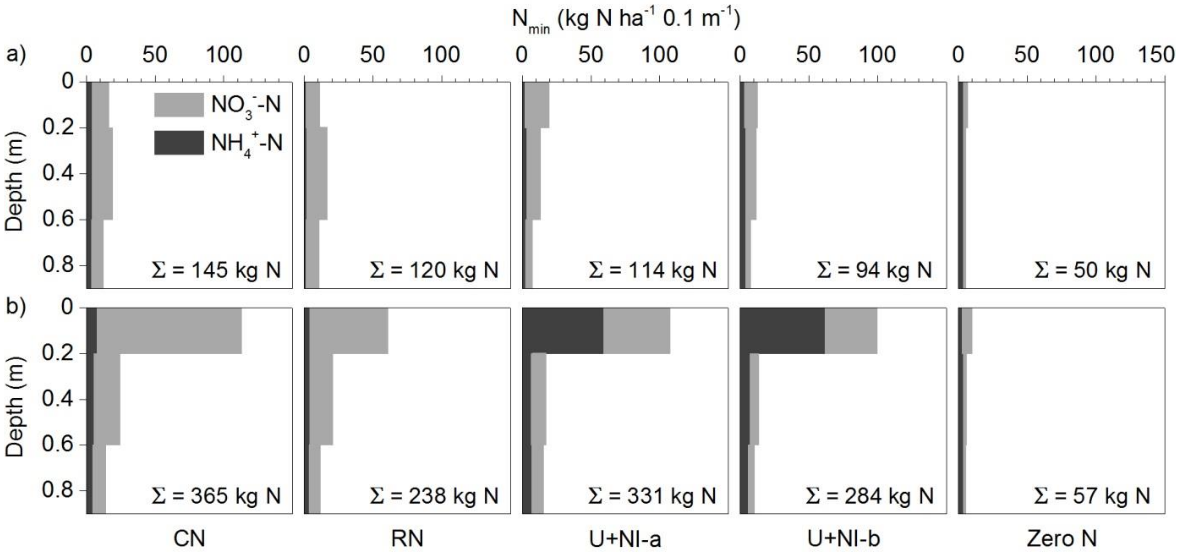

Figure 4.5: Mean N_{min} (NO_3^--N and NH_4^+-N) contents in 0-0.9 m depth in 0.1 m depth increments before shooting fertilization in a) WW09/10 (20 March 2010) and b) WW10/11 (10 March 2011) in Huai'an, China (bars: mean values; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment).

4.4. Discussion

The stabilization of urea fertilizers with a NI is an efficient measure for the reduction of N losses and the increase of NUE in many cropping systems (Prasad and Power 1995; Subbarao et al. 2006). Thus, to decrease the typically high N losses from the rice-wheat double crop rotation in northern Jiangsu Province, the nitrification inhibitor DCD could be a good mitigation option. Recent studies in the southern Jiangsu Province (Hofmeier et al., 2015) have shown that the total fertilizer N application rate of pure urea can be reduced by 15 to 25 % to summer rice and by 20 to 25 % for winter wheat compared to the farmers' fertilization practice without any yield decline. In the present study, we observed an even slightly higher reduction potential for the rice-wheat system in northern Jiangsu compared to the south and also found a distinct effect of the application of urea treated with DCD on plant growth, N uptake, NUEs and soil N dynamics. However, these effects differ considerably between the two crops and years with different weather conditions.

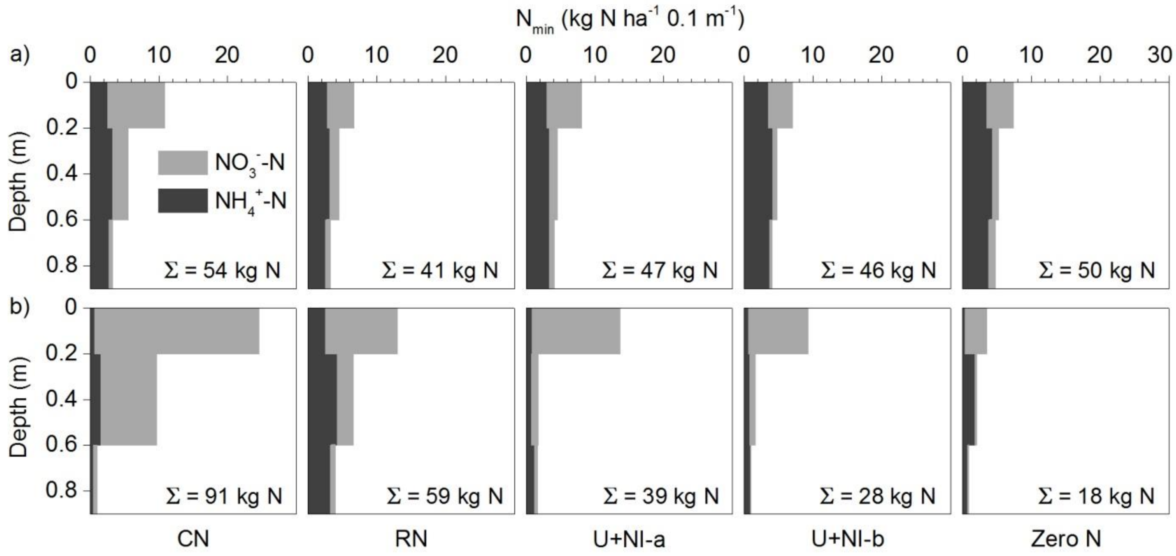

Figure 4.6: Mean N_{min} (NO_3^--N and NH_4^+-N) contents in 0-0.9 m depth in 0.1 m depth increments after wheat harvest in a) WW09/10 (14 June 2010) and b) WW10/11 (16 June 2011) in Huai'an, China (bars: mean values; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment).

4.4.1. Summer rice crop growth and yield

A significant effect of the NI on rice grain yield could not be observed in both years, as yields under U+NI-a were only slightly higher compared to the corresponding urea treatments with the same total N fertilizer application (CN in SR09 and RN in SR10). The positive effect of the NI on plant growth under U+NI-a in SR09 can be partly attributed to an increase in the tiller number during active tillering (Figure A.3) and thus a higher panicle number compared to the other treatments. This stimulation of the tiller formation led to an increased grain yield, N uptake and higher RE_N. However, with the reduced N application rate under U+NI-b, the tiller formation during tillering stage and thus the panicle number decreased. This effect was partly compensated by a higher percentage of filled spikelets and a higher TGW compared to CN and U+NI-a, but the achieved mean grain yield was still lower. Similar compensation mechanisms were observed under zero N. Thus, a further reduction of the total N application than applied to U+NI-a cannot be recommended under the current agronomic and fertilization practice (broadcasting into standing ponded water) and with the varieties currently grown. The effect of NI was less pronounced in SR10 compared to SR09. Grain yields, N uptake and agronomic indices differed only slightly between the NI treatments and RN. However, a distinct advantage of the reduced application of N fertilizers became clear in SR10, because under CN the lodging risk was much higher compared to the other treatments. Heavy lodging that took place at the end of SR10, led to a clear yield decrease, due to more complications during mechanized harvesting of the crops displaced from the vertical.

To summarize, our agronomic analyses did not show a distinct and consistent effect of DCD amendment to urea on rice grain yield over both seasons. This was also the result of a meta-analysis by Linquist et al. (2013) who reported that DCD is not effective in increasing rice yields which may be caused by the degradation of DCD with increasing temperature, as the half-life of DCD is reduced to 20 days in soils at 25°C (Kelliher et al. 2008). However, in another meta-analysis, Qiao et al. (2015) showed that NI application significantly increased productivity of rice grain yield by 7 % and that DCD increased plant productivity for all considered cropping systems, except for vegetables. These differences in observations on the effect of NIs on rice grain yield suggests that a yield response to a NI only occurs under situations where N is lost by leaching or denitrification and if those losses result in a N deficiency that is sufficient to reduce crop yields without the NI (Frye 2005; Sahrawat 1980).

4.4.2. Winter wheat crop growth and yield

The effect of the NI on plant growth and N uptake of winter wheat was strongly influenced by weather conditions and thus growth conditions during the wheat season. While grain yields under U+NI-a were similar to the urea treatment with the same total N amount (RN) in WW08/09, yields were significantly higher in WW09/10. Thus, a significant effect of the NI on N uptake and yield formation of winter wheat can be expected for WW09/10. Moreover, even with a reduction of the total fertilizer rate under U+NI-b by 40 % compared to CN, similar grain yields were achieved. The winter temperatures during the wheat season WW10/11 were very low and precipitation from sowing in November to shooting stage in March was less than 60 mm. Thus, the weather conditions during WW10/11 had a negative influence on overall crop development and yield formation. This led to a very patchy crop stand and a strongly reduced plant growth until the end of March 2011. The yield level of all treatments was much lower than in WW09/10 and especially under zero N the grain yield was extremely low.

The weather conditions during the first wheat season (WW09/10) were very favorable for crop growth and the average yield level of the N treatments was 1.2 Mg ha^{-1} higher in WW09/10 than in WW10/11. The cumulative precipitation from November to March in WW09/10 amounted to 180 mm, which is three times higher than in WW10/11, and the mean temperature was 0.4°C higher compared to WW10/11. However, due to the high cumulative precipitation and 5 heavy rain events in WW09/10 it can be expected, that a considerable amount of N_{min} in the soil was leached under the root zone during the winter or was lost via nitrification/denitrification processes due to the wet soil conditions and high clay content. As a consequence, the N_{min} contents in the topsoil (0-0.2m) before the fertilizer application in March 2010 ranged between 22 kg N ha^{-1} under RN to 40 kg N ha^{-1} under U+NI-a. Thus, N deficiency followed by reduced crop growth can be expected for the NI treatments as no N fertilizers were applied here before shooting. In contrast, a third top dressing was applied to CN and RN in March 2010 that had a distinct effect on N uptake and grain yield. This shows, that the NI treated fertilizer that was applied during tillering stage was not effective enough to stabilize the ammonia-N in WW09/10 and that a further top dressing before shooting was favorable for yield formation. Thus, a delayed application of the second top dressing to the NI treatments can be recommended.

Similar to our result, previously reported field studies did not find any consistent effect of NIs on plant growth and N uptake. A meta-analysis by Abalos et al. (2014) showed that grain yield and NUE of cereals (incl. rice) can be significantly increased with the application of NIs. However, they pointed out that the effectiveness was dependent on the environmental and management factors of the evaluated studies. They found a larger response in coarse-textured soils, in irrigated systems and in crops with high fertilizer N application rates. An increase in grain yield and N uptake after DCD application compared to the application of pure urea was also reported by Liu et al. (2013a) for winter wheat in a wheat-maize double crop rotation in NCP as well as by Ma et al. (2013) for the wheat crop in a rice-wheat system in the Taihu Region. However, in a study with the focus on the rice-wheat system in India, Banerjee et al. (2002) found no effect of DCD addition to urea on grain yields and N uptake but reported that NH_3 volatilization increased in wheat after application of DCD.

4.4.3. Mineral N during the rice season

The mineral N content in agricultural soils is mainly influenced by soil and climate conditions, N mineralization, crop and fertilizer management, and crop N uptake. Due to the anaerobic conditions in the puddled rice field, nitrification takes place only to a very limited extent and most of the mineral N is present as NH_4^+ in the soil, with very little NO_3^- contents in oxidized zones at the soil surface, in the rhizosphere and during mid-season aeration (Keeney and Sahrawat 1986; Prasad and Power 1995). Therefore, a direct effect of the NI application on N_{min} dynamics in the paddy soil during the rice season were not expected and could not be observed. The NO_3^--N content in the puddled soil layer was below the detection limit (data not shown) throughout both rice seasons and leaching losses of NO_3^--N are expected to be negligible due to the low NO_3^--N contents and the compacted plough pan with little permeability. However, the application of urea with NI can significantly decrease N_2O emissions during the rice growing season (Asing et al. 2008; Ding et al. 2015; Li et al. 2009; Majumdar et al. 2000) because NH_4^+ can be nitrified to NO_3^- during the drainage of standing water and significant nitrification can be expected after the application of fresh irrigation water containing a high level of dissolved O_2 (Kumar et al. 2000). Emission of N_2O can thus be reduced most efficiently by the application of NIs at active tillering before midseason aeration (Li et al. 2009). Moreover, as nitrification is expected to be the most important source of N_2O emissions in the experimental soil (Lan et al. 2013), the use of nitrification inhibitors might be a good option to mitigate N_2O emissions. Additionally, greenhouse gas emissions from paddy fields also decrease with the application of NI compared to plain urea, due to the significant decrease in CH_4 emissions (Ghosh et al. 2003; Li et al. 2009; Linquist et al. 2012; Pasda et al. 2001). This can be explained by an assumed detrimental effect on methanogens (Pathak et al. 2003) and a stimulation of CH_4 oxidation (Weiske et al. 2001).

Corresponding to the observed plant parameters, the NH_4^+-N contents in the soil differed considerably between the two summer rice seasons. In SR09, high crop N uptake in all N treatments led to similar and relatively low NH_4^+-N contents in the puddled soil layer and the soil solution of all N treatments. However, large differences were not expected between CN, RN and U+NI-a in SR09 because the fertilizer N amount was the same among these treatments. The NH_4^+-N contents in SR09 increased only after the first top dressing with urea due to the application of NPK fertilizer with a low ammonium content (9 % NH_4^+-N and 6 % NO_3^--N). In SR10, crop N uptake was much lower compared to SR09 and thus the NH_4^+-N contents in the soil were considerably higher. This was most pronounced during tillering stage when NH_4^+-N contents up to 70 mg NH_4^+-N kg^{-1} were measured under CN. The higher NH_4^+-N contents from 11 to 15 DAT under CN and RN compared to the NI treatments can be partly explained by the higher N application rate at early tillering to CN and by a lower crop N uptake under RN following the earlier fertilizer N application in the demonstration experiment.

4.4.4. Mineral N in the soil during the winter wheat season

After drainage of the flooded rice fields before rice harvest, the soil becomes aerobic and the nitrification process is initiated. Therefore, residual N_{min} in 0-0.9 m after rice harvest consists of both, NH_4^+ and NO_3^-. In our study, the residual N_{min} content ranged between 50 and 80 kg N ha^{-1}, depending on plant N uptake (Fig S5). Compared to the N_{min} content after rice harvest that were reported for other rice growing regions in China (e.g. Taihu Region), where soil horizons were usually nearly depleted (Hofmeier et al. 2015; Roelcke et al. 2002; Roelcke et al. 2004) the residual N_{min} content we found at the end of the rice season in northern Jiangsu was considerably higher and should be considered in the fertilizer management of the wheat crop.

Several studies have shown that NO_3^- and NH_4^+ contents in the soil during winter wheat season can effectively be regulated by the application of NI. The delayed nitrification of NH_4^+, leads to higher ratios of NH_4^+ to NO_3^- in the soil following applications of ammoniacal fertilizers with NI than without the amendment of a NI (Boeckx et al. 2005; Ding et al. 2015; Ma et al. 2013). However, this effect is strongly dependent on weather conditions. Elevated precipitation and soil temperatures decreases the effectiveness of most NIs (Subbarao et al. 2006). As there were no enhanced NH_4^+-contents in the soil profiles of the NI treatments observed before fertilizer application during tillering and before shooting stage in WW09/10 it can be expected that DCD was faster degraded than in WW10/11 and that the effectiveness of the NI was reduced due to the relatively high temperatures in January and the high precipitations in February. In contrast, the extremely dry and cold weather conditions from November 2010 until March 2011 led to an increased half-life of DCD and thus to significantly increased NH_4^+ contents in the NI treatments before shooting fertilization. However, also NO_3^--N contents were much higher in WW10/11 than WW09/11, in particular in the topsoil of CN and RN treatments, because fertilizer granules from basal fertilization were not completely dissolved and partly remained at the soil surface until first top dressing. The extremely high N_{min} contents in January 2011 before the commonly practiced fertilizer application during tillering stage were additionally caused by the late sowing of the wheat crop (in mid-November 2010) with the consequence of a reduced plant development and thus lower crop N uptake during the winter months.

4.4.5. Recommendations for the application of NI

Based on the results from the field experiment we observed that the use of a NI had a more pronounced effect on grain yields and NUE of upland winter wheat compared to irrigated summer rice and that the number of split applications to winter wheat could be reduced by one compared to farmers' practice. However, the effect on crop growth and yield formation was not consistent in the two observed winter wheat seasons and it has to be expected that the efficiency of a NI under these agronomic conditions is more pronounced in years with extreme weather conditions. Correspondingly, a distinct effect of the NI application on N_{min} dynamics in the soil was only observed during the second winter wheat season (2010/11), when crop growth was negatively affected by exceptional weather conditions. The results suggest that mineral N fertilization can be reduced to 225 and 180 kg N ha^{-1} to rice and wheat, respectively, if a NI is added. Nitrogen fertilization should be split into three applications to rice (60 % of the total N amount until maximum tillering and 40 % at panicle initiation) and two application to wheat (40 % of the total N amount before sowing and 60 % at late tillering stage or before shooting). The topdressing to winter wheat during tillering stage should be applied depending on weather conditions and plant growth but preferably not before mid-February. Mineral N contents should ideally be determined before the fertilization at shooting stage of winter wheat in spring as recently recommended for the fertilizer application to winter wheat in the NCP (Cui et al. 2010b; Hartmann et al. 2014; Zhang et al. 2012). However, this is seldom applied in China so far (e.g., Zhang et al., 2009.).

Deterrents for a wide adoption of enhanced-efficiency fertilizers such NIs for the fertilization of field crops are numerous. The most important one is surely that conventional urea fertilizers are comparatively cheap due to the subsidies for fertilizer production. Chinese smallholder farmers tend to apply mineral N fertilizers in excessive amounts as an ‘insurance’ against high N losses and the risk of yield decline in years with extreme weather conditions. To them, it would appear to be more economic to apply additional N than using a NI with a reduced amount on total N fertilizer. However, the introduction of such fertilizers would be easy to implement as there is no special technique required and they can be handled like other fertilizers. Furthermore, the reduction in the number of split applications would reduce the workload for smallholder farmers, which is an important additional benefit.

4.4.6. Conclusions

The presented results of our two-year field experiment showed that the application of stabilized urea treated with DCD in the rice-wheat double cropping system in eastern China can have positive effects on grain yield and NUEs of upland winter wheat crops with a reduced N application rate by 28 % compared to the farmers’ practice. Moreover, the number of split applications to winter wheat could be reduced by one compared to farmers’ practice. However, this effect was not consistent in the two observed winter wheat seasons and it has to be expected that the efficiency increases in years with extreme weather conditions. Yield reductions of wheat occurred due to N deficiency during shooting stage and thus fertilizer application of NI treated urea during tillering stage should be applied depending on weather conditions and plant growth but preferably not before mid-February. The effect of the NI on crop growth and yield formation of the summer rice crop was less pronounced compared to wheat. However, we pointed out that the N application can be distinctly reduced by 25 % compared to the farmers’ practice with and without the use of a NI but a further reduction cannot be recommended under the current agronomic and fertilization practice. A possible advantage of the application of NIs can, however, be seen in the reduction of greenhouse gas emissions from the flooded rice fields.

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5. Synopsis and conclusions

5.1. General discussion

Proper N fertilizer management is essential in the intensive rice-wheat double cropping systems in eastern and southeastern China to improve the resource efficiency and to clearly reduce the environmental impact of Chinese agriculture. Management strategies to reduce N input and losses have to be developed that are easy to adapt for small-scale farmers and that have no negative impact on grain yield and farmers' income. Only if these preconditions are fulfilled there is a chance that recommendations will be accepted by policy makers and implemented by farmers. Mitigation strategies have to comprise fertilizer, soil and crop management in order to optimize the cropping system as a whole and to develop more comprehensive approaches for the reduction of N losses to the environment. Field experiments on farmers' field sites give valuable information on the status and the impact of the current agricultural practices and provide the possibility to investigate different management strategies under practical conditions.

This thesis examined different strategies to mitigate environmental N losses from the highly over-fertilized rice-wheat double cropping system in eastern and southeastern China. Based on field experiments at two representative locations, it provided a detailed overview of the N loss potential and N use efficiency of current farmers' fertilization practices, develops strategies for an optimized fertilizer management and analyses the N dynamics in the soil of this cropping system (Section 2 and 3). Recommendations for optimized agronomic practices were given and as an example, the possibilities for a better management of crop residues were evaluated (Section 3). Moreover, as a more specific strategy to enhance the NUE and reduce the N losses in the rice-wheat system, the application of urea in combination with a nitrification inhibitor was investigated (Section 4).

5.1.1. The rice-wheat system in eastern and southeastern China

The field trials were conducted at two different locations in Jiangsu Province that are representative for the current situation of intensive Chinese agriculture. The Taihu Region located in southern Jiangsu and northern Zhejiang Provinces and Shanghai Municipality is one of the most economically developed areas of China and one of the regions with the highest urbanization level of the country. Enormous expansion of urban areas and industrial sites led to losses of highly fertile agricultural soils in the recent years and significant changes in the income structure decreased the economic importance of agriculture. This region is characteristic for the rapid social, economic and environmental transformations that occurred in China in the past three decades. In contrast to the Taihu Region, northern Jiangsu Province is economically less developed and agriculture has still a very high importance in this region's income structure. Moreover, northern Jiangsu has gained in importance for the overall food-security of China as most of the productive soils are still available for agricultural production. As a consequence of urbanization and rapid loss of arable land, land use pressure on limited agricultural soils is constantly growing with the steadily increasing need for a higher productivity of Chinese agriculture.

The comparison of soil properties, crop growth under zero N treatment and the indigenous N supply clearly showed that growth conditions and N loss potential differed considerably between the two sites. While the soil in Huai'an (northern Jiangsu Province) had a silty clay texture (clay content > 40 %), was moderately alkaline with a pH of 8.3 and had free carbonates throughout the profile, the soil in Yixing (Taihu Region) had a silt loam texture and was acidic with a pH of 5.4. The average rice yield under zero N was more than 2 Mg ha^{-1} higher in Yixing (6.38 Mg ha^{-1}) compared to Huai'an (4.37 Mg ha^{-1}) and, correspondingly, the average N uptake by summer rice without mineral N supply (121 kg N ha^{-1} in Yixing) differed by more than 40 kg N ha^{-1} between the two sites. This indicates the very high indigenous N supply (INS) to irrigated summer rice in the Taihu Region by irrigation water from the adjacent canals, the high atmospheric N deposition and mineralization of organic N from the highly fertile soils in this region. However, an additional reason for the higher plant N uptake in Yixing might be the strong fixation of NH_4^+-N in the soil in Huai'an due to the high clay content leading to a higher immobilization of applied fertilizer N and lower plant availability (Nieder et al. 2011). The distinct yield effect of N fertilization at both sites clearly shows that in spite of the high N balance surplus of the rice-wheat system, no accumulation of surplus N in mineral or organic form, that could be released and become plant available for the subsequent crops, occurs in the soil. Instead, most of the surplus N is rapidly lost to the atmosphere via NH_3 volatilization and nitrification/denitrification processes. As a consequence, N fertilization has to precisely match the crop N demand or fertilizers have to be stabilized by amendments or proper agricultural practices.

The average grain yield of winter wheat under zero N was roughly the same at the two sites in Jiangsu Province, with only 0.2 Mg ha^{-1} higher yields in Yixing (3.62 Mg ha^{-1}) compared to Huai'an (3.43 Mg ha^{-1}). In contrast, there was a 20 kg N ha^{-1} higher N uptake under zero N observed in Huai'an and, moreover, nearly 20 kg N ha^{-1} more residual N_{min} were found in the soil in Huai'an under zero N after wheat harvest. This indicates a larger INS during the wheat season in Huai'an that is probably derived from a higher N mineralization rate in the soil at Huai'an than Yixing. This is supported by an aerobic long-term laboratory incubation experiment that was carried out over 182 days with field-moist soils from the two sites (Hofmeier et al. 2012). A distinctly higher N mineralization in the topsoil was observed for the Huai'an compared to the Yixing soil, which can be explained by higher soil organic matter and clay contents and may have led to the higher N uptake of winter wheat in Huai'an. However, this had no positive effect on grain yields. Lower grain yields in Huai'an compared to Yixing might be caused by the very clay-rich plough pan that might impeded wheat root growth. By this way, it has less access to nutrients in the whole soil profile, and wheat therefore takes up it nutrients largely from the topsoil. This makes it much more dependent on heavy doses of readily available mineral fertilizer-N. This should be considered in the development of optimized fertilization strategies for Huai'an.

5.1.2. Evaluation of current N fertilization practices

The evaluation of the current N fertilization practices showed distinct differences between the two contrasting study regions in Jiangsu Province. For the Taihu Region, a beginning decrease in fertilizer application rates to summer rice was already reported by Roelcke et al. (2004). Fertilizer N application decreased from 330 to 360 kg N ha^{-1} in the mid-1990s to 240-280 kg N ha^{-1} in 2001 and this trend continued to the current N application rate of 240 kg N ha^{-1}. A somewhat smaller reduction rate was observed for winter wheat from approximately 250 kg N ha^{-1} in 2002/2003 (Roelcke et al. 2004) to the current farmers' practice of 220 kg N ha^{-1}. Directly affected by this trend was the N balance surplus of the whole rice-wheat crop rotation that decreased from 335 kg N ha^{-1} in the mid-late 1990s (Richter and Roelcke 2000) to roughly 250 kg N ha^{-1} in the early 2000s (Roelcke et al. 2004) and further to the currently observed 140 kg N ha^{-1}. This development was partly achieved by an increased environmental awareness of government officials and farmers (Roelcke et al. 2004) and by the introduction of improved wheat varieties and high-NUE rice cultivars with an improved N uptake rate and a higher grain yield production per unit of nutrient (Chen et al. 2015; Fageria et al. 2008; Good et al. 2004; Wang et al. 2009). Moreover, "land consolidation" is strongly encouraged and facilitated by the Chinese government. According to Yan, Xiaoyuan (pers. comm., 2014) N fertilizer application rates have been dropped in southern Jiangsu due to some specialized farmers now managing larger field plots merged from the previous small plots of smallholder farmers.

While the fertilizer N amount applied to the rice-wheat rotation in Wuxi City (of which Yixing Country is a part) already decreased in the past 10 to 15 years, the N application rates in Huai'an are still at a very high level with 300 kg N ha^{-1} applied to summer rice and 250 kg N ha^{-1} to winter wheat. Despite the higher N input in northern Jiangsu, the mean grain yield and total N uptake of one whole crop rotation was considerably lower here compared to the field experiment conducted in the Taihu Region. As a consequence, the calculated indicators for NUE were lower in the north and the N balance surplus of 320 kg N ha^{-1} yr^{-1} was comparable to that reported for the Taihu Region in the mid-1990s by Richter and Roelcke (2000). Main N loss pathways from the calcareous soil in northern Jiangsu during the wheat season are NH_3 volatilization after surface application of urea fertilizer and nitrification/denitrification processes due to wet soil conditions (Ju et al. 2009). Results from a laboratory incubation experiment with the soils from Yixing and Huai'an showed that N_2O and NO emission rates are substantially higher in Huai'an (Lan et al. 2014), that nitrification here is the most important source for N_2O emissions (Lan et al. 2013) and they emphasized the high N_2O loss potential of the alkaline soil in Huai'an. Moreover, a large part of the residual N_{min} contents after winter wheat harvest are prone to losses, particularly by leaching and denitrification during flooding of the field for the subsequent rice crop. Therefore, mitigation strategies to reduce N losses to the environment should aim to reduce this residual N_{min} content as much as possible.

5.1.3. Optimized fertilizer management strategies

In this thesis detailed management strategies for an efficient use of mineral N fertilizers were developed for the rice-wheat double-crop rotation in eastern and southeastern China in order to enhance the NUE and to reduce the potential N losses to the environment. The focus of the management strategies lay on the amount of total applied N, the timing of fertilizer application, the N amount of single split-applications and on the stabilization of the widely used urea fertilizer with a nitrification inhibitor. The recommendations on fertilizer management could easily be adopted by small-scale farmers as they do not depend on the introduction of new machineries or innovative agricultural practices, except for the application of urea in combination with a nitrification inhibitor. However, for a wider application it is essential to raise awareness for the relationship between high fertilizer N application and the environmental impact of N losses and between agricultural practices and soil fertility.

For the Taihu Region, a yield level of 8 to 10 Mg ha^{-1} for summer rice and 5 to 7 Mg ha^{-1} for winter wheat can be expected. To achieve these yields, it was shown above that the N application rate to rice could be reduced by 15 to 25 % of the current farmers' fertilization practice and should range between 200 and 230 kg N ha^{-1}. The total N amount should be split in 3 applications with 20, 35 and 45 % of total N at sowing, tillering and panicle initiation, respectively. The residual N_{min} content after wheat harvest is not to be taken into account for the fertilization planning of the rice crop as most of it is lost via leaching and denitrification. Nitrogen fertilization to winter wheat in the Taihu Region has an even higher reduction potential compared to rice and can be reduced by 20 to 25 % of the current farmers' practice. Most of this reduction should be conducted at basal fertilization and the first top-dressing. The recommended N fertilization of 170 to 180 kg N ha^{-1} should be split into 3 applications with one-third of the total N amount to basal, during tillering and before shooting stages, respectively. The residual N_{min} content after rice harvest, ranging between 20 and 40 kg N ha^{-1}, can be fully taken into account for the derivation of basal fertilizer application rate. The results showed that around 20 % of fertilizer N could easily be saved during the whole double-crop rotation with an appropriate fertilizer management. The environmental N loss potential in the Taihu Region can thus be reduced by nearly 90 kg N ha yr^{-1} without yield depression. The NUE can in turn significantly be increased here.

In northern Jiangsu, the yield level of summer rice ranges between 7 and 9 Mg ha^{-1} and is slightly lower compared to the Taihu Region. For winter wheat, similar yield levels were observed for northern as for southern Jiangsu (5-7 Mg ha^{-1}). Based on this thesis' results a N application rate for summer rice in Huai'an ranging between 225 and 240 kg N ha^{-1} is recommended, equivalent to a reduction by 20 to 25 % compared to farmers' practice. The total N amount should be split in 3 application events with 20, 40 and 40 % at transplanting, tillering and panicle initiation, respectively. Thus, nearly 90 % of the N fertilizer reduction was adopted at the split applications during early and maximum tillering stage. The reduction potential for the application of N fertilizers to winter wheat in northern Jiangsu is slightly higher compared to the rice crop, a situation similar to the wheat crop in the Taihu Region. According to the field trials' results, the N rate to winter wheat should be reduced by 25 to 30 % compared to the farmers' practice and should range between 180 and 195 kg N ha^{-1}. And again, the necessity for reduction is highest for the basal application, as more than 150 kg N ha^{-1} is applied before sowing of the wheat under conventional fertilization practice but N uptake during the winter (November-March) is less than 60 kg N ha^{-1}. Moreover, as the residual N_{min} content after rice harvest ranged between 35 and 65 kg N ha^{-1}, it has to be fully taken into account for the derivation of basal fertilization of winter wheat. For the whole double crop rotation in northern Jiangsu, the average N amount that can be easily saved is around 25 % and the potential N losses can be reduced by more than 140 kg N ha^{1} yr^{-1} without negative effects on grain yields and with significant increases of NUE.

5.1.4. Further options for enhancing NUE and agronomic practices

In addition to the evaluation of the environmental impact of the current fertilization practices and the development of optimized fertilizer management strategies, the application of urea in combination with the nitrification inhibitor DCD and 1H-1,2,4-triazol (commercially available as ALZON® 46) was tested as an option to stabilize the applied N and to enhance the NUE and reduce N losses in the rice-wheat system in northern Jiangsu. The results showed that the use of a NI had a more pronounced effect on grain yields and NUE on wheat compared to rice and that the number of split applications to winter wheat could be reduced by one compared to farmers' practice. However, the effect on crop growth of winter wheat was not consistent in the two observed years and it has to be expected that the efficiency of a NI under these agronomic conditions is more pronounced in years with extreme weather conditions. Correspondingly, a distinct effect of the NI application on N_{min} dynamics in the soil was only observed during the second winter wheat season (2010/11), when crop growth was negatively affected due exceptional weather conditions. The results suggest that mineral N fertilization can be lowered by 25 and 28 % to rice and wheat, respectively, compared to the farmers' practice if a NI is added. Nitrogen fertilization should be split into three applications to rice (60 % of the total N amount until maximum tillering and 40 % at panicle initiation) and two application to wheat (40 % of the total N amount before sowing and 60 % at late tillering stage). The introduction of such fertilizers would be easy to implement as there is no special technique required and they can be handled like other fertilizers. Furthermore, the reduction in the number of split applications would reduce the workload for smallholder farmers, which is an important additional benefit. A possible advantage of the use of urea together with a NI to summer rice can be expected in the reduction of greenhouse gas emissions from flooded soils that was reported in several studies (Abalos et al. 2014; Akiyama et al. 2010; Ding et al. 2015; Frye 2005; Subbarao et al. 2006). However, deterrents for a wide adoption of enhanced-efficiency fertilizers such NIs for the fertilization of field crops are numerous. The most important one is surely that conventional urea fertilizers are comparatively cheap due to the subsidies for fertilizer production. Chinese smallholder farmers tend to apply mineral N fertilizers in excessive amounts as an 'insurance' against high N losses and the risk of yield decline in years with extreme weather conditions. To them, it would appear to be more economic to apply additional N than using a NI with a reduced amount on total N fertilizer.

The development and evaluation of optimized management strategies for the application of mineral N fertilizers to the rice-wheat system is an important step to reduce environmental N losses from agricultural soils in an intensive cropping system in southeastern China. However, another significant source of environmental pollution is the frequent practice of burning the crop residues of the proceeding crop directly on the field prior to sowing the subsequent crop. As a consequence, organic C and N that could potentially contribute to increasing soil fertility and plant nutrient, is lost to the atmosphere. Additionally, the concentration of particulate matter (PM) in the air increases drastically by straw burning after harvest. Therefore, proper strategies for the management of crop residues in the rice-wheat double cropping system can contribute to reducing these atmospheric emissions and maintaining organic C and N from straw in the soil-plant system. The incorporation of chopped straw is a common straw treatment practice in many agricultural systems but rarely carried out in the rice-wheat rotations in southeastern China due to farmers' concerns about adverse effects on crop establishment and plant growth. In contrast to these concerns, no such negative effect was observed for winter wheat or summer rice in this thesis' investigations carried out over 2 years. The incorporation of straw could easily be performed with the existing machinery since most combine harvesters in China are now equipped with such a device. However, it has to be noted that the incorporation of crop residues is particularly recommended for the rice straw before the wheat crop due to the good feasibility, the high fertilizer-N equivalent of about 85 % of the organically bound N if rice straw is incorporated in combination with mineral N fertilizers (Cassman et al. 1998) and the potentially reduced N_2O emissions (Ma et al. 2010). Taking this N source into account (approx. 40 kg N ha^{-1}) and considering the residual N_{min} content in the soil after rice harvest (approx. 50 kg N ha^{-1} in our experiment) in the fertilizer planning for the wheat crop, this would result in a significant reduction in additional mineral N fertilizer to be supplied. In contrast to the management of rice crop residues, the management of wheat residues during irrigated lowland rice presents a considerably bigger challenge due to the very short fallow period between wheat and rice and the low economic off-field value of wheat straw (Bijay-Singh et al. 2008). Moreover, as the incorporation of wheat residues into the flooded rice soil stimulates CH_4 emission during the rice season (Ma et al. 2009; Yan et al. 2005) and increases NH_3 volatilization after urea application (Wang et al. 2012), alternative options for the wheat straw use should be examined.

5.2. Scientific Outlook

The field experiments conducted for this thesis provided a detailed insight into the environmental impact of the current fertilization practice of Chinese small-scale farmers in the rice-wheat double crop rotation. This thesis pointed out the high N loss potential of common farming practices and allowed to give recommendations for optimized fertilizer management strategies. However, an efficient use of N fertilizers is only possible if other plant nutrients like P and K are readily available (Zhu and Chen 2002) and a balanced fertilization is necessary in order to improve the NUE and to reduce the N balance surpluses. Both experimental soils of the two sites in Jiangsu Province had a “low” available P content in the topsoil (11-14 mg kg^{-1}) according to Sun et al. (2009). Therefore, P deficiency might have had negative influences on plant growth and thus N uptake. Consequently, further investigations on P availability and optimization of P fertilization are crucial for an efficient use of fertilizer N.

In addition to the optimization of the crop nutrient supply, more effort has to be put on the development of enhanced fertilizer application techniques that can easily be adapted by farmers. Most small-scale farmers in China still broadcast urea fertilizers by hand to the soil surface and do not incorporate it into the soil. With this practice NH_3 emissions are promoted (Cai 1997; Cai et al. 1998; Cao et al. 2013) and a uniform distribution of fertilizers is difficult to achieve, specialized application equipment has to be developed that suits field conditions in the rice-wheat cropping system. Applied amount of N fertilizers could be better adjusted, distributed more accurately and, with the adequate technique, placed directly into the soil.

However, as urea is the most important N fertilizer used in the rice-wheat system that is readily available and comparatively cheap due to high subsidies (Ju et al. 2009; Zhu et al. 2006), more emphasizes should be put on the management of this N-source. As a first step, detailed directives like ‘codes of best agricultural practice’ for urea-fertilization have to be formulated including guidelines on the application of urea as basal fertilizer (i.e. incorporation), application as top dressing and instructions about the best application period (i.e. application preferably before significant rainfall).

As a complement to this, the application of urea in combination with a urease inhibitor (UI) to the rice-wheat system has to be further investigated. Due to the high NH_3 loss potential of urea fertilizers applied to soils with a neutral-high pH and broadcasting in standing ponded water under high temperatures, the stabilization of urea by inhibiting the enzyme urease and slowing down the hydrolysis to NH_4^+-N, can efficiently reduce NH_3 volatilization (Abalos et al. 2012; Linquist et al. 2013; Xu et al. 2002). Several studies reported that grain yield and NUE can be significantly increased and NH_3 losses can be reduced by the application of urea in combination with a UI (Li et al. 2015; Sanz-Cobena et al. 2011; Zaman et al. 2009). Moreover, if urea is applied in combination with a NI, an increase in NH_3 emissions can be promoted on soils with high pH and if the fertilizer is not incorporated into the soil and the NH_4^+-N remains on the soil surface. Under those conditions, that are usually found during fertilizer application to winter wheat in northern Jiangsu, the additional amendment of a UI would have a high potential to increase the NUE and reduce N losses significantly.

In addition to the fertilizer recommendations based on field experiments, model based recommendations can help to determine and evaluate best management practices. This could be done by the process-based, dynamic N simulation model HERMES (Kersebaum 1995, 2007; Kersebaum and Beblik 2001) that has already been calibrated for the conditions in the North China Plain (Michalczyk et al. 2014). First steps were taken to adjust the HERMES model for the conditions of the winter wheat crop in the rice-wheat system in eastern China (Hofmeier et al. 2012; Hofmeier et al. 2013). The model was also calibrated with the dataset of the static field experiment in Huai'an (northern Jiangsu) and showed reasonable results for N_{min} dynamics and water contents in the aerobic soil during the winter wheat season. Furthermore, the total biomass, grain yields and N uptake of winter wheat under different N fertilization treatments could be well simulated. However, the model still needs to be calibrated for the conditions in southern Jiangsu and validated against other data sets from field experiments in southeastern China. Therefore, until now, the irrigated rice crop cannot be simulated with the HERMES model. A simulation of the whole rice-wheat cropping sequence with the transitions between flooded and non-flooded soil environments and the corresponding soil C and N dynamics was recently implemented in the APSIM model (Gaydon et al. 2009; Gaydon et al. 2012) by implementing of the rice crop components from the ORYZA2000 rice model (Bouman and Van Laar 2006).

5.3. Conclusions

Referring to the objectives of this thesis, the presented results provided a detailed overview of the current fertilization practice of Chinese small-scale farmers in the rice-wheat double cropping system in eastern and southeastern China. Distinct differences were observed in field experiments between the two study sites with regard to cropping practice, N fertilization, NUEs and N balance surpluses. Potential N losses to the environment have been decreasing in the Taihu Region in the past decades while the N surpluses in northern Jiangsu are still extremely high. However, due to the alternately flooded and non-flooded soil environments in this cropping system, N transformation losses are high at both sites with most of the surplus N being lost to the atmosphere via NH_3 volatilization and nitrification/denitrification processes. Thus, optimized N management strategies have to aim at achieving a better congruence between N application and crop N demand or at reducing N losses by stabilization of the applied N.

Based on the field experiments, recommendations on N fertilizer application for the rice-wheat crop rotation were developed in this thesis in order to increase NUE and mitigate N losses to the environment. An enhancement of all analysed indicators for the NUE, namely the AE_N, RE_N and PFP_N, could be achieved and a reduction of the N balance surplus, as an indicator for the N loss potential to the environment, was possible without any significant yield decline in both study regions. It was highlighted that the emphasis of fertilizer N reduction should be placed on the basal N fertilization for winter wheat and on the N fertilizer applications during the tillering stage for summer rice. The reduction potential for mineral N fertilizer application was somewhat higher for winter wheat compared to summer rice at both sites in Jiangsu Province and distinctly higher in northern compared to southern Jiangsu. Furthermore, the considerable amount of residual N_{min} left in the soil after the rice harvest in northern Jiangsu has to be considered by farmers when planning the fertilization of the following winter wheat crop. With the optimized fertilizer management, a distinct reduction of the residual N_{min} content after the winter wheat crop that is prone to N leaching and denitrification losses could be achieved.

Additionally to the development of different fertilizer management strategies, with an emphasis on the optimization of current fertilization practices, it was investigated in this thesis whether the application of urea treated with a nitrification inhibitor is suitable to increase NUE and reduce N losses. This enhanced-efficiency fertilizer aims to stabilize the ammonium-N and to reduce the risks for environmental N losses through nitrate leaching and gaseous losses via denitrification. A positive effect on NUEs, grain yields and via the reduction of farmers' labour requirements could be achieved for both crops, although the effects on crop growth were not consistent across the two years. It could be shown that the efficiency of the application of a nitrification inhibitor strongly depended on the actual weather conditions and that grain yields could be maintained efficiently in years with extreme weather.

A reduction of N losses to the environment occurring from fertilizer N application is urgently needed in China and the development of optimized fertilizer management strategies has highest priority. However, for a sustainable intensification of the Chinese agriculture, all nutrient sources as well as environmental pollutants have to be considered. Thus the investigation of proper strategies for the management of crop residues aimed to reduce the overall environmental impact of agricultural practices. It could be shown, that incorporation of rice straw before the wheat crop can easily be performed, had no adverse effect on crop growth and a potentially positive effect on soil fertility.

To conclude, this thesis contributed to a better understanding of the growth conditions and N dynamics in the rice-wheat double cropping system in eastern and southeastern China and highlighted the huge environmental N loss potential of current agricultural practices. Recommendations for optimized fertilizer management strategies as well as for agronomic practices were given and it was shown that a considerable reduction of N fertilization is possible without any yield decline.

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Appendix A

Application of a stabilized mineral nitrogen fertilizer in the rice-wheat double-crop rotation in eastern China – Field experiment using a nitrification inhibitor

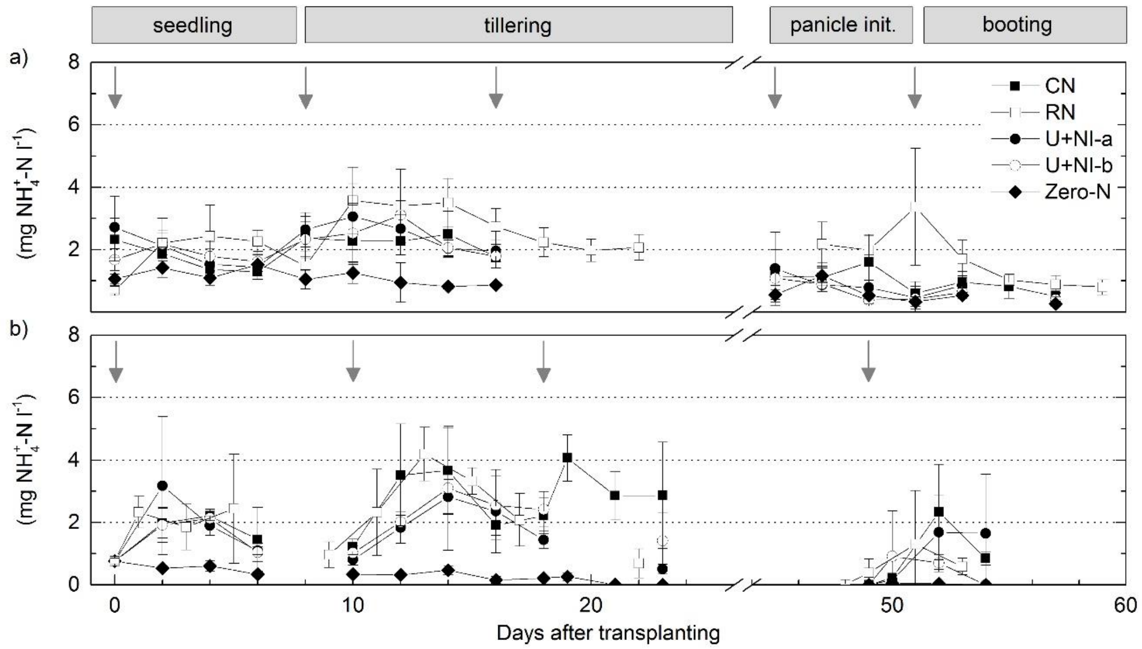

Figure A.1: Time course of mean NH_4^+-N contents in soil solution expressed as mg NH_4^+-N per liter of puddled layer (0-0.2 m) during summer rice season 2009 (a) and 2010 (b) in Huai'an, China (error bars: ± s.d.; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment; arrows indicate fertilizer application events; crop growth stages are shown at the top).

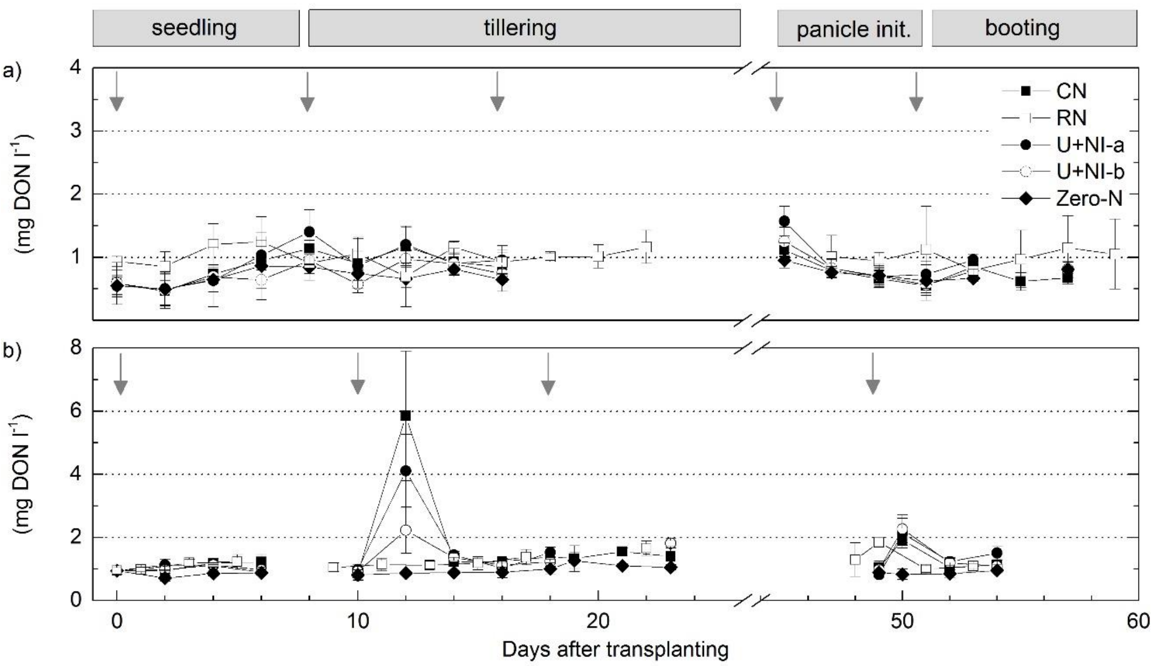

Figure A.2: Time course of mean DON contents in soil solution expressed as mg DON per liter of puddled layer (0-0.2 m) during summer rice season 2009 (a) and 2010 (b) in Huai'an, China (error bars: ± s.d.; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment; arrows indicate fertilizer application events; crop growth stages are shown at the top).

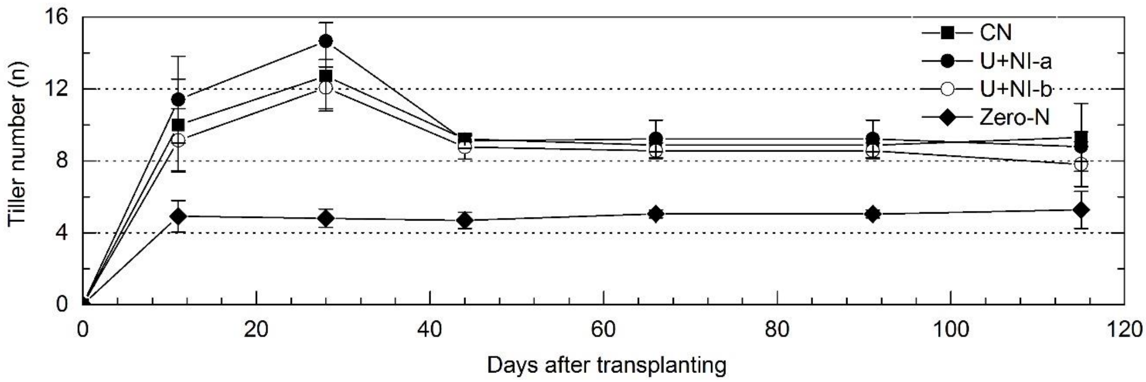

Figure A.3: Mean tiller number of summer rice crops 2009 (SR09) in Huai'an, China (bars: mean values; error bars: ± s.d.; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N)).

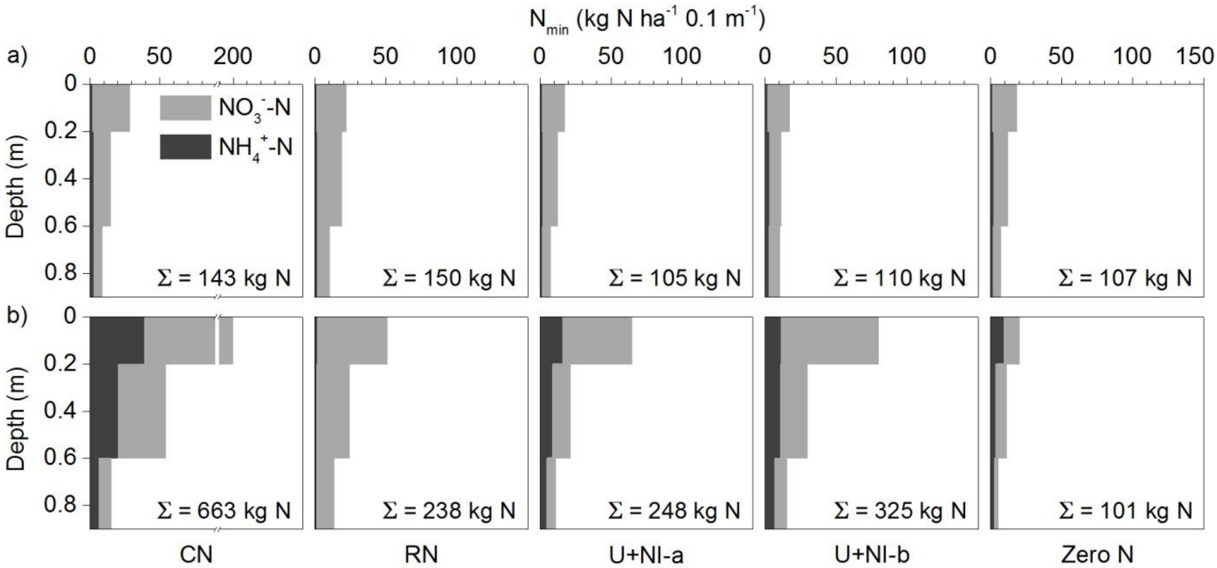

Figure A.4: Mean N_{min} (NO_3^--N and NH_4^+-N) contents in 0-0.9 m depth in 0.1 m depth increments before regreening fertilization in a) WW09/10 (19 January 2010) and b) WW10/11 (14 January 2011) in Huai'an, China (bars: mean values; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment).

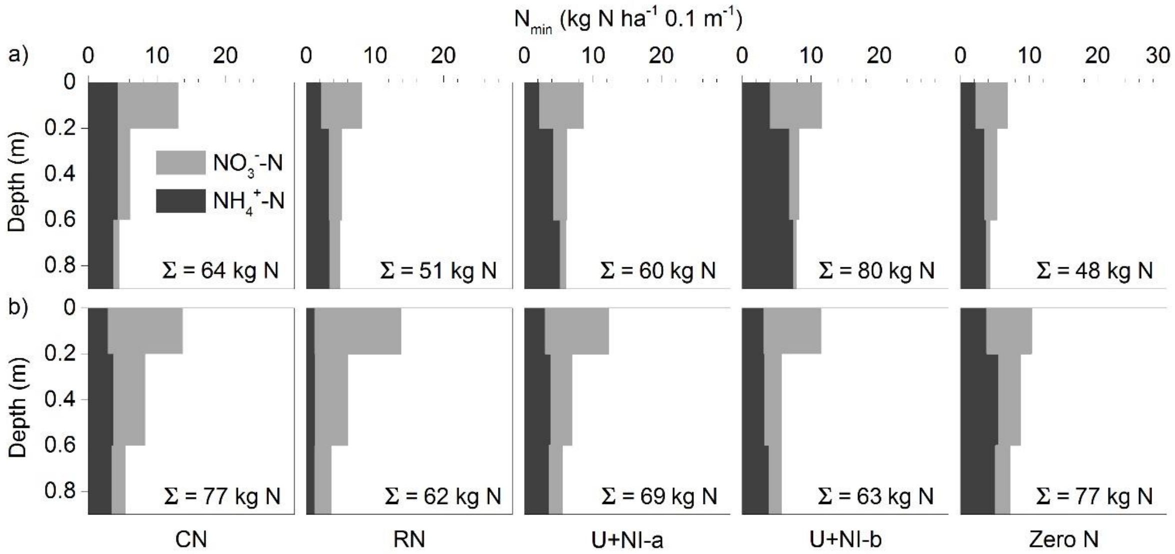

Figure A.5: Mean N_{min} (NO_3^--N and NH_4^+-N) contents in 0-0.9 m depth in 0.1 m depth increments after rice harvest in a) SR09 (23 October 2009) and b) SR10 (29 October 2010) in Huai'an, China (bars: mean values; n=4 for conventional N fertilization (CN), urea with nitrification inhibitor (U+NI) and N-omission plots (zero N), n=5 for reduced N fertilization (RN) from adjacent demonstration field experiment).

Appendix B

Curriculum vitae

Personal details

Name	Maximilian Hofmeier
Date/place of birth	07. November 1979 in Munich (Germany)
Nationality	German

Work experience

2016 – present	Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL)
2012 – 2015	Institut für Pflanzenbau und Bodenkunde, Julius Kühn-Insitut
2008 – 2011	Institut für Geoökologie, Technische Universität Braunschweig

Education

2000 – 2007	Studies of Biology (diplom), Universität Hamburg
1999	Abitur, Gymnasium Hummelsbüttel in Hamburg

Appendix C

List of publications

Publications in peer-reviewed journals

Hofmeier, M., M. Roelcke, Y. Han, T. Lan, H. Bergmann, D. Böhm, Z.C. Cai und R. Nieder (2015): Nitrogen management in a rice-wheat system in the Taihu Region: Recommendations based on field experiments and surveys, *Agriculture, Ecosystems & Environment 209 (Special Issue), 60-73, doi: 10.1016/j.agee.2015.03.032*

Publications in non-peer-reviewed journals

Hofmeier, M., M. Roelcke, Y. Han, Z.C. Cai, C. Schuster, M. Fuchs und R. Nieder (2014): Testing of a stabilized nitrogen fertilizer in a rice-wheat double-crop rotation in southeastern China, *In: Cordovil, C.M.d.S. (Ed.) Proceedings of the 18th Nitrogen Workshop - The nitrogen challenge: building a blueprint for nitrogen use efficiency and food security. 30th June - 3rd July 2014, Lisboa, Portugal, pp. 191-193*

Hofmeier, M., T. Lan, Y. Han, M. Roelcke, Z.C. Cai und R. Nieder (2013): Minderung von Stickstoff-Transformationsverlusten in einer Reis-Weizen Doppelfruchtfolge in Südostchina, *In: Jahrestagung der DBG, Böden- Lebensgrundlage und Verantwortung, 7. - 12. September 2013, Rostock*

Hofmeier, M., M. Roelcke, H. Yong, Z.C. Cai und R. Nieder (2012): Nitrogen mineralization potentials in rice-wheat systems in southeastern China, *In: Richards, K.G., Fenton, O., Watson, C. J. (Eds) Proceedings of the 17th Nitrogen Workshop – Innovations for sustainable use of nitrogen resources. 26th – 29th June 2012, Wexford, Ireland, pp. 176-177*

Hofmeier, M., Y. Han, M. Roelcke, C. Schuster, M. Fuchs, Z. Cai und R. Nieder (2011): Anwendung eines stabilisierten N-Düngers in einer Reis-Weizen Doppelfruchtfolge in Südostchina. *In: Jahrestagung der DBG, Böden verstehen - Böden nutzen - Böden fit machen, 3. - 9. September 2011, Berlin*

Hofmeier, M., Y. Han, M. Roelcke, H. Tang, Z. Cai und R. Nieder (2009): Innovatives Stickstoffmanagement und innovative Düngetechnologien in den intensiv genutzten Reis-Anbausystemen Südostchinas. *In: Jahrestagung der DBG, Böden – eine endliche Ressource, 5. - 13. September 2009, Bonn*

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